

A Comparison of EnergyPlus and eQUEST
Whole Building Energy Simulation Results for a
Medium Sized Office Building
by
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ABSTRACT

With the increasing interest in energy efficient building design, whole building energy simulation programs are increasingly employed in the design process to help architects and engineers determine which design alternatives save energy and are cost effective. DOE-2 is one of the most popular programs used by the building energy simulation community. eQUEST is a powerful graphic user interface for the DOE-2 engine. EnergyPlus is the newest generation simulation program under development by the U.S. Department of Energy which adds new modeling features beyond the DOE-2's capability.

The new modeling capabilities of EnergyPlus make it possible to model new and complex building technologies which cannot be modeled by other whole building energy simulation programs. On the other hand, EnergyPlus models, especially with a large number of zones, run much slower than those of eQUEST. Both eQUEST and EnergyPlus offer their own set of advantages and disadvantages. The choice of which building simulation program should be used might vary in each case. The purpose of this thesis is to investigate the potential of both the programs to do the whole building energy analysis and compare the results with the actual building energy performance. For this purpose the energy simulation of a fully functional building is done in eQUEST and EnergyPlus and the results were compared with utility data of the building to identify the

degree of closeness with which simulation results match with the actual heat and energy flows in building.

It was observed in this study that eQUEST is easy to use and quick in producing results that would especially help in the taking critical decisions during the design phase. On the other hand EnergyPlus aids in modeling complex systems, producing more accurate results, but consumes more time. The choice of simulation program might change depending on the usability and applicability of the program to our need in different phases of a building's lifecycle. Therefore, it makes sense if a common front end is designed for both these simulation programs thereby allowing the user to select either the DOE-2.2 engine or the EnergyPlus engine based upon the need in each particular case.

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Chapter 1

INTRODUCTION

Energy simulation tools are increasingly used for analysis of energy performance of buildings and the thermal comfort of their occupants.

Today, there are many building performance simulation programs with different user interfaces and different simulation engines that are capable of these analyses. Given the significant variety of such simulation tools, it is crucial to understand limitations of the tools and the complexity of such simulations. The reliability of data exchange and straightforward, user-friendly interfaces are major aspects of the practical usage of these tools. Due to the huge amount of data that is to be input and the availability of rich 3D geometry rendering engines, effective data exchange and software interfaces are crucial to enable faster and reliable performance of the simulation tools..

DOE-2 is one of the most popular programs used by the building simulation community. With today's PC computing power, a DOE-2 energy model normally takes less than a minute or couple of minutes in case of large buildings to complete an annual simulation run. DOE-2's computational efficiency results from its hour by hour calculations and the sequential software structure of LOADS-SYSTEMS-PLANT-ECONOMICS which does not solve the building envelope thermal dynamics with the HVAC system operating performance simultaneously. EnergyPlus is a new generation simulation program built upon the best features of DOE- 2

and BLAST, and adds new modeling features beyond the two programs. With DOE-2's limitations in modeling emerging technologies, more modelers, especially in academia and research community, have begun using EnergyPlus for their simulation needs. EnergyPlus does sub-hourly calculations and integrates the load and system dynamic performance into the whole building energy balance calculations which can provide more accurate simulation results but runs much slower compared with DOE-2. Both the programs offer their own set of advantages and disadvantages. The purpose of this study is to analyze the capabilities of these two programs by developing energy models of a same building with similar simulation settings in both the software and comparing their results.

Purpose and Objectives

For the past 50 years, a wide variety of building energy simulation programs have been developed, enhanced and are in use throughout the building energy simulation community. These building energy simulation programs have different features and various capabilities such as: general geometry modeling; zone internal loads; building envelope properties, daylighting and solar; infiltration, ventilation and multi-zone airflow; renewable energy systems; electrical systems and equipment; HVAC systems; HVAC equipment; environmental emissions; economic evaluation; climate data availability, results reporting and validation.

Nearly all energy analysis tools have been targeted at mechanical engineers and code compliance specialists. Architects need tools that provide qualitative or “order of magnitude” feedback in a highly graphical form to show clients.

Software tools that integrate graphical results with context-sensitive guidance are likely to have the most appeal for architects. In contrast, engineers need software tools that can be used in both the conceptual design stage, when little is known about the building; as well as in the final design stages, when most project details have been finalized. Software, such as eQUEST, and DesignBuilder, that combine simplified input wizards with detailed simulation tools have the most potential to meet these differing needs at various stages of the design process.

Certain programs are designed to work for individual building components like the wall, roof, building form and fenestration. There are also tools which are specifically used for one or more parameters like lighting, heat transfer, wind, and shade. When a building is modeled for a same climate in different simulation programs, the performance of the building shown as the output of the simulation run is expected to be same, but in actual they exhibit a difference in output. Hence, there is need for comparison of output, and analyze by what percent they are deviating.

The objectives of this study are as follows:

- To understand eQUEST and EnergyPlus software.

- Model the building similarly in both the software, by closely mapping the input parameters
- Compare the results of both the programs with measured utility data and identify discrepancies.
- Document the observations from the project.

Methodology

The purpose of the research is to perform energy simulation of a fully functional building for identifying the degree of closeness with which simulation results generated by two different simulation tools match with actual heat and energy flows. The case of a medium sized office building, in Albuquerque, NM has been used for this purpose. Further the analysis has been extended to study the energy savings for a set of ECMs.

The methodology used in the project has the following steps:

- Explore EnergyPlus and eQUEST programs.
- Data collection about the office building
- Preparation of schedules for occupancy, lighting and computers using actual data
- Understand the inputs parameters in both the tools
- Develop a detailed building energy simulation model of the case using eQUEST and EnergyPlus.
- Modification of weather data file required for simulation using on-site measurements

- Comparison of results derived from both the simulation programs with the utility data of the building.

Scope and Limitations

As different simulation programs may have different software architecture, different algorithms to model building and energy systems, and require different user inputs even to describe the same building envelope or HVAC system component; it is an enigmatic task to develop an identical energy model with two simulation programs. To get as close as possible for an apple-to-apple comparison of both the simulation programs, they will be run on a common basis with:

- The same building and energy systems and their control strategies
- Studied for the same simulation run period
- The same or as close as possible simulation settings: time step, calculation algorithm.
- The same computer with same hardware and software configurations

Evaluation of the two programs in question will be based on the following:

Usability - Import/export capabilities; the user interface; how much time is spent for learning and training; effort required in updating model / conducting parametric studies and the simulation run time.

Functionality - The detail of comprehensiveness of geometric and system modeling;

Reliability - Consistency and accuracy of results

Prevalence -Available documentation, user support and pricing and licensing

The analysis in this project is limited to the study of the results. In depth analysis of the reasons for deviation based on the structure/algorithms of the programs are not done in this project.

The degree of instrumentation in this project is also limited.

Computer configuration

The simulation runs are done on a personal laptop computer with Intel Core 2 Duo processor of 3 GHZ and 2 GB of RAM on Microsoft Windows Vista operating system with SP2.

Chapter 2

LITERATURE STUDY

Introduction

Buildings are complex physical objects. They interact with their immediate surroundings while trying to provide a comfortable living and working environment to the occupants. The way a building behaves and performs is affected by the choices made in selecting building materials and components while designing the building envelope (walls, windows, roofs), and different systems (lighting, HVAC, etc.). Buildings provide comfortable indoor environment conditions like thermal, visual, and acoustical by consuming energy.

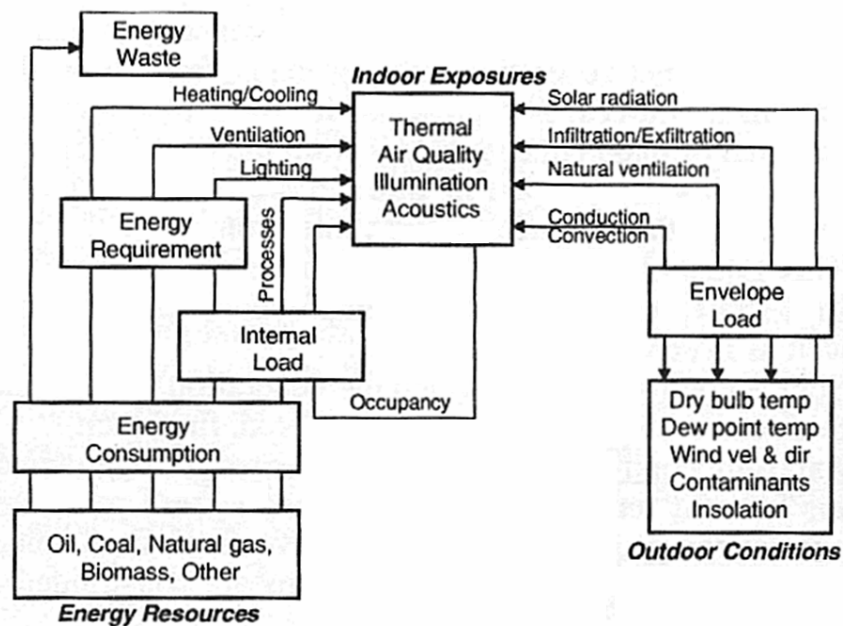


Figure1. Energy flow and concepts in buildings

Building energy simulation

In recent years, the variables affecting energy use have increased manifold and understanding building behavior has become a daunting task. However, technological advancements in computer software have provided tools that are more effective at predicting energy performance once the building is operational. An energy simulation tool models the thermal, visual, ventilation and other energy consuming processes taking place within a building to predict its energy and environmental performance. During its calculation process, it takes into account the external climatic factors, internal heat sources, building materials and systems to accurately model the building. Building energy simulation is a powerful method for studying energy performance of buildings and for evaluating architectural design decisions as well as choices for construction materials and methods. Complicated design issues can be examined and their performance can be quantified and evaluated.

Simulation and energy analysis are essential to designers in developing effective forms and components for their buildings. Building energy simulation is an analysis of the dynamic energy performance of a building using computer modeling and simulation techniques. Such tools support the integrated use of multiple investigation and visualization during the design evolution process—from the conceptual and schematic phases to the detailed specification of building components and systems. There is a wide range of simulation tools available today which help

predict various aspects of building behavior such as energy performance, acoustical performance, fire movement, anti-seismic performance, life-cycle assessment simulators, etc.

- Energy performance simulation tools allow designers to:
- Predict thermal behavior of buildings in relation to its outdoor environment.
- Envisage the impact of daylight and artificial light inside buildings.
- Model the impact of wind pattern and ventilation create natural scenarios and impact on energy use.
- Estimate the size/capacity of equipment required for thermal and visual comfort.
- Calculate the effect of various building components on each other and predict resulting conditions.
- Check for compliance with building codes.
- Consider the building as a single integrated system.

Building energy simulation has been playing an increasingly significant role not only in building design, but also in operation, diagnostics, commissioning and evaluation of buildings. It can help designers compare various design options and lead them to energy efficient designs in manner of cost-effectiveness. Building energy simulation can also help facility managers and engineers identify energy

saving potentials and evaluate the energy performance and cost-effectiveness of energy saving measures to be implemented. There are many building energy simulation software available now a days. Some are simplified energy analysis tools that only provide a quick analysis of annual energy use of buildings, but some use more detailed models and run on hourly basis that provide detailed hour-by-hour energy analysis of buildings. No matter which software is used, calibration of simulation models is necessary and crucial for the accuracy and usability of energy simulation. The calibration process compares the results of the simulation with measured data and tunes the simulation until its results closely match the measured data. Whole building simulation tools are widely used and are applied to the entire building as an integrated system; these take into account all parameters and components together. Examples of the programs include:

- Simplified programs for overall energy consumption assessment, peak temperature prediction, heating/cooling loads calculations.
- Sophisticated programs for hourly simulation of heat, light and air movement.
- Complex specialist packages for daylighting and artificial lighting, computational fluid dynamics (CFD), two- and three-dimensional conduction calculations, and moisture migration within the building components.

Simulation tools and comparison

A large number of simulation tools have been developed over the last few decades. The building energy simulation software tool web page, run by the US Department of Energy lists over 240 tools, ranging from research grade software to commercial products. Some important studies and comparisons were previously done on some of these tools that are discussed below.

(Pasqualetto, 1997) presented a case study of a multiple-step validation undertaken to test the MICRO-DOE2.1E program, which includes the following: (i) response of the model to a given perturbation in the outdoor environment, (ii) comparison with another modeling tool, (iii) sensitivity analysis, and (iv) empirical validation using information from a large existing office building.

(Crawley, 2008) describe testing and validation of EnergyPlus. The results to date show good agreement with well established simulation tools such as DOE-2.1E, BLAST, and ESP. Several testing utilities have been developed to help automate the task of assuring that each new version of the software is still performing properly. Selected test results are presented along with lessons learned.

(Neymark, 2002) stated that validation of building energy simulation programs consists of a combination of empirical validation, analytical verification, and comparative analysis techniques.

(Henninger, 2004) gives the report of testing the EnergyPlus building energy simulation software using the IEA HVAC BESTEST E100–E200 series of tests. HVAC BESTEST is a series of steady-state tests for a single-zone DX cooling system. Cases range from dry to wet coil, low to high part load, and low to high temperatures. This published test suite includes three sets of analytical solutions and results from several other simulation programs for comparison.

(Crawley, 2005) provides an overview of a report, which provides up-to-date comparison of the features and capabilities of twenty major building energy simulation programs. The comparison is based on information provided by the program developers in the following categories: general modeling features; zone loads; building envelope and daylighting and solar; infiltration, ventilation and multizone airflow; renewable energy systems; electrical systems and equipment; HVAC systems; HVAC equipment; environmental emissions; economic evaluation; climate data availability, results reporting; validation; and user interface, links to other programs, and availability.

(Zhou, 2008) evaluate the energy performance of the VRV air-conditioning system, a new simulation module is developed and validated experimentally in this study, on the basis of the building energy simulation program, EnergyPlus. The differences between average monitored and predicted data for the total cooling energy and power use are proved to be within 25.19% and 28.31%, respectively.

Comprehensive testing of building energy analysis software is a difficult task given the infinite combinations of inputs that may be entered and the difficulties in establishing truth standards for all but the simplest cases. Testing has been guided by a comprehensive test plan which includes the following types of tests:

- Analytical tests which compare against mathematical solutions,
- Comparative tests which compare against other software,
- Sensitivity tests which compare small input changes versus a baseline run,
- Range tests which exercise the program over wide ranges of input values,
- Empirical tests which compare against experimental data.

EnergyPlus

U.S Department of Energy funded the development of a new building energy-simulation program beginning in 1996 and called it EnergyPlus. While the program borrows what was effective from BLAST and DOE-2, it contains a number of quite innovative features, including sub hourly time steps, user-configurable modular HVAC systems that are integrated with a heat and mass balance-based zone simulation, as well as input and output data structures that can facilitate third party module

and interface development. EnergyPlus was released in April 2001 (EnergyPlus, 2008).

EnergyPlus structure

In 1997, two workshops on next generation energy tools sponsored by DOE and the U.S. Department of Defense, revealed a strong consensus that a more flexible and robust tool with additional capabilities was needed. Recurrent simulation needs expressed throughout both workshops focused on design, environment, economics, and occupant comfort and safety. Designers need tools that provide answers to very specific questions during design. They want tools that provide the highest level of simulation accuracy and detail that is reasonably possible without getting in the user's way. One of the highest priorities was an integrated (simultaneous loads and systems) simulation for accurate temperature and comfort prediction.

In response to these findings, it was decided that integrated simulation should be the underlying concept for EnergyPlus. Loads calculated (by a heat balance engine) at a user-specified time step (10 mm to 1 hr) are passed to the building systems simulation module at the same time step. This module, with a variable time step (down to seconds), calculates heating and cooling system and plant and electrical system response. Feedback from the building

systems simulation module on loads not met is reflected in the next time step of the load calculations in adjusted space temperatures, if necessary.

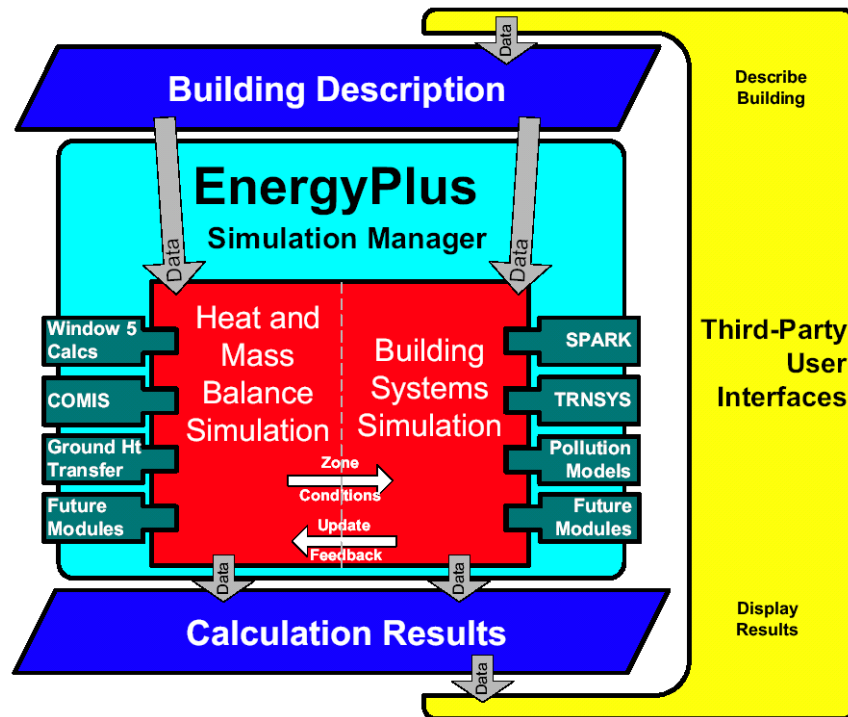


Figure 2. Structure of EnergyPlus

By using an integrated solution technique in EnergyPlus, the most serious deficiency of the BLAST and DOE-2 sequential simulations were solved: inaccurate space temperature prediction due to a lack of feedback from the HVAC module to the loads calculations. Accurate prediction of space temperatures is crucial to energy-efficient system Engineering--system size, plant size, occupant comfort, and occupant health are dependent on space temperatures.

EnergyPlus also contains inter-zonal airflow, moisture absorption and desorption, definitions of more realistic HVAC system controls and radiant heating and cooling systems. In addition, EnergyPlus enables automated sizing of many component-specific parameters.

EnergyPlus simulation is mainly based on input from text files, which increases the effort to define all necessary input data compared to engines with graphical user interfaces. Some user interfaces are under development and the most advanced of them are DesignBuilder and Open Studio. The heat and thermal mass balance simulation is integrated with the building systems simulation, such that the result is always accurate and independent of space loads being met or not. In addition, modules such as COMIS, SPARK, TRANSYS and others can easily be incorporated into the simulation to combine different concepts and aspects of building energy simulation. This modular approach allows the integration of additional modules in the future.

EnergyPlus Key Capabilities

The following is a representative list of EnergyPlus capabilities:

- **Integrated, simultaneous solution** where the building response and the primary and secondary systems are tightly coupled (iteration performed when necessary)
- **Sub-hourly, user-definable time steps** for the interaction between the thermal zones and the environment; variable time steps for interactions between the thermal zones and the HVAC systems (automatically varied to ensure solution stability)
- **ASCII text based weather, input, and output files** that include hourly or sub-hourly environmental conditions, and standard and user definable reports, respectively
- **Heat balance based solution** technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at both in the interior and exterior surface during each time step
- **Transient heat conduction** through building elements such as walls, roofs, floors, etc. using conduction transfer functions

- **Improved ground heat transfer modeling** through links to three-dimensional finite difference ground models and simplified analytical techniques
- **Combined heat and mass transfer** model that accounts for moisture adsorption/desorption either as a layer-by-layer integration into the conduction transfer functions or as an effective moisture penetration depth model (EMPD)
- **Thermal comfort models** based on activity, inside dry bulb, humidity, etc.
- **Anisotropic sky model** for improved calculation of diffuse solar on tilted surfaces
- **Advanced fenestration calculations** including controllable window blinds, electrochromic glazings, layer-by-layer heat balances that allow proper assignment of solar energy absorbed by window panes, and a performance library for numerous commercially available windows
- **Daylighting controls** including interior illuminance calculations, glare simulation and control, luminaire controls, and the effect of reduced artificial lighting on heating and cooling
- **Atmospheric pollution calculations** that predict CO₂, SO_x, NO_x, CO, particulate matter, and hydrocarbon production for both on site and remote energy conversion

DesignBuilder

The DesignBuilder is the most popular interface developed for EnergyPlus that includes a simplified CAD interface, templates, wizards, and most compact air system configurations of EnergyPlus.

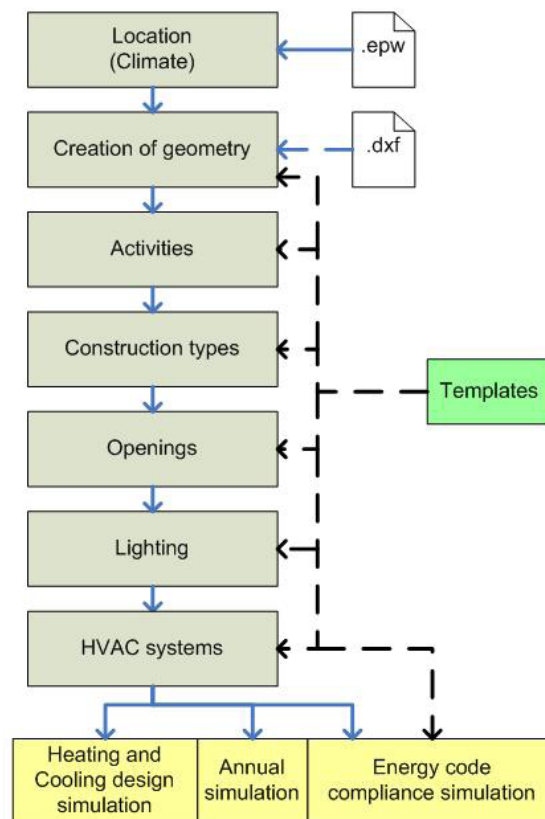


Figure 3. Work flow of DesignBuilder

The workflow of DesignBuilder starts with the selection of a location and the corresponding weather through a weather file followed by the creation of specific thermal building model geometry with the integrated CAD interface. This building geometry represents the definition of geometry needed for the simulation of

the building's thermal performance. Additionally, one can import DXF files as footprints for the creation of the geometric model.

DesignBuilder provides a variety of country or region specific templates for selection of parameters (such as materials and constructions). Lists of other definable parameters include internal loads (with occupancy patterns/activities), construction types, openings (windows and doors), lighting, and HVAC systems. Once the definition of all input parameters is complete, one can perform design day and/or annual simulations. In addition, one can validate most parts of the thermal model of the building against the energy code that applies to the location of the building.

The typical usage of DesignBuilder includes evaluation of facade options, daylighting analysis, visualization of site layouts and solar shading, thermal simulation of natural ventilation, and sizing of HVAC equipment and systems

Open Studio

Open Studio Plug-in for Google Sketch Up is another front end to EnergyPlus that was created by the National Renewable Energy Laboratory for the U.S. Department of Energy, that allows users to create and edit the building geometry for the EnergyPlus input files. This free plug-in also allows users to launch EnergyPlus simulations and view the results without leaving the Google Sketch

Up 3D drawing program. The plug-in adds the building energy simulation capabilities of EnergyPlus to the Sketch Up environment. One can launch an EnergyPlus simulation of the model they are working on and view the results without leaving Sketch Up.

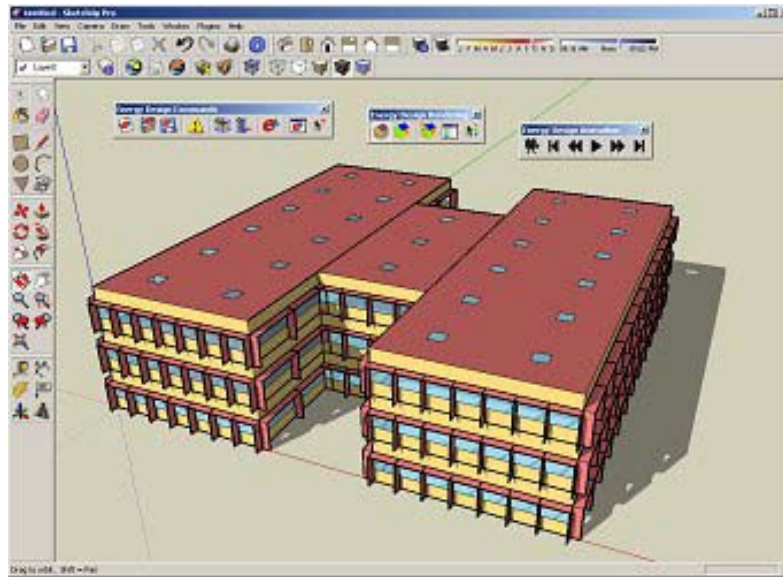


Figure 4. Screen shot of Sketch Up with Open Studio plug-in

Highlights of Open Studio Plug-in include the ability to:

- Create and edit EnergyPlus zones and surfaces
- Launch EnergyPlus and view the results without leaving Sketch Up
- Match interzone surface boundary conditions
- Search for surfaces and sub surfaces by object name
- Add internal gains and simple outdoor air for load calculations
- Add the ideal HVAC system for load calculations

- Set and change default constructions
- Add daylighting controls and illuminance map

EnergyPlus has been tested with several test suites including:

- Analytical Tests
- HVAC tests, based on ASHRAE Research Project 865
- Building fabric tests, based on ASHRAE Research Project 1052 Comparative Tests
- ANSI/ASHRAE Standard 140-2004
- International Energy Agency Solar Heating and Cooling Program BESTest (Building Energy Simulation Test) methods
- EnergyPlus HVAC Component Comparative tests
- EnergyPlus Global Heat Balance tests

eQUEST

eQUEST is an easy to use building energy analysis tool which provides high quality results by combining a building creation wizard, an energy efficiency measure wizard and a graphical results display module with an enhanced DOE-2.2 derived building energy simulation program. The building creation wizard walks a user through the process of creating a building model. Within eQUEST, DOE-2.2 performs an hourly simulation of the building based on walls, windows, glass, people, plug loads, and

ventilation. DOE-2.2 also simulates the performance of fans, pumps, chillers, boilers, and other energy-consuming devices. eQUEST allows users to create multiple simulations and view the alternative results in side-by-side graphics. It offers energy cost estimating, daylighting and lighting system control, and automatic implementation of energy efficiency measures (eQUEST, 2008).

Integrated Energy Design

While DOE-2 has long been available for designers to evaluate the energy performance of their building designs, it has been too difficult and expensive to use for most projects. eQUEST is a building energy simulation tool so comprehensive that it would be useful to all design team members, yet so intuitive any design team member could use it, in any or all design phases, including schematic design. eQUEST is well named because it provides something the buildings industry has been looking for, but has been unable to find a sophisticated, yet easy-to-use building energy analysis tool powerful enough to address every design team member's domain (e.g., architectural, lighting, mechanical) but simple enough to permit a collaborative effort by all design team members in all design phases. eQUEST was designed to allow to perform detailed analysis of today's state-of-the-art building technologies using today's most sophisticated building energy use simulation techniques without requiring extensive experience in the

"art" of building performance modeling. This is possible because eQUEST's DOE-2-derived engine is combined with a building creation wizard, an energy efficiency measure wizard, industry standard input defaults, and a graphical results display module. eQUEST will step through the creation of a detailed building model, allow to automatically perform parametric simulations of design alternatives and provide with intuitive graphics that compare the performance of design alternatives. Reliable detailed simulation was made easier by eQUEST.

Engine in eQUEST

DOE-2 is the most widely recognized and respected building energy analysis program. Although DOE-2 was first released in the late 1970's, it used as starting points earlier simulation tools and methods developed and funded by ASHRAE, NASA, the U.S. Postal Service, and the electric and gas utility industries. During the first half of the 1980's, it continued under DOE support, but decreasing national concern about energy created the need for industry support, which became its principal source of support through much of the 1990's. Through this long and collaborative history, DOE-2 has been widely reviewed and validated in the public domain. The simulation "engine" within eQUEST is derived from the latest official version of DOE-2, however, eQUEST's

engine extends and expands DOE-2's capabilities in several important ways, including: interactive operation, dynamic/intelligent defaults, and improvements to numerous long-standing shortcomings in DOE-2 that have limited its use by mainstream designers.

Overview of the Process

eQUEST calculates hour-by-hour building energy consumption over an entire year (8760 hours) using hourly weather data for the location under consideration. Input to the program consists of a detailed description of the building being analyzed, including hourly scheduling of occupants, lighting, equipment, and thermostat settings. eQUEST provides very accurate simulation of such building features as shading, fenestration, interior building mass, envelope building mass, and the dynamic response of differing heating and air conditioning system types and controls. eQUEST also contains a dynamic daylighting model to assess the effect of natural lighting on thermal and lighting demands. The simulation process begins by developing a "model" of the building based on building plans and specifications. A base line building model that assumes a minimum level of efficiency (e.g., ASHRAE 90.1) is then developed to provide the base from which energy savings are estimated. Alternative analyses are made by making

changes to the model that correspond to efficiency measures that could be implemented in the building. These alternative analyses result in annual utility consumption and cost savings for the efficiency measure that can then be used to determine simple payback, life-cycle cost, etc. for the measure and, ultimately, to determine the best combination of alternatives.

Building Blocks of Simulation

Building simulation requires that a model of the proposed building be created not a physical model but a virtual model capable of simulating the important thermodynamics of the proposed building. Toward that end, the following list summarizes essential components, steps, or building blocks, in a how-to description of the process of simulation modeling. Before "building" anything, including simulation model, first considers and collects the following

Analysis Objectives

Approach for simulation model with a clear understanding of the design questions wish to answer must be clear. It has to focus on the important issues and at the same time, limit the questions with use of model to answer. Experience will teach how best to strike this important balance for each new project.

Building Site Information and Weather Data

Important building site characteristics include latitude, longitude and elevation, plus information about adjacent structure or landscape capable of casting significant shadows on proposed (or existing) building.

Building Shell, Structure, Materials, and Shades

eQUEST is interested in the walls, roof, and floor of proposed building only in so far as they transfer or store heat. Geometry (dimensions) and construction materials of each of the heat transfer surfaces of proposed building. This will include glass properties of windows and the dimensions of any window shades (e.g., overhangs and fins). eQUEST provides users with simple, user-friendly, choices for each of these.

Building Operations and Scheduling

This includes information about when building occupancy begins and ends (times, days of the week, and seasonal variations such as for schools), occupied indoor thermostat set points, and HVAC and internal equipment operations schedules. eQUEST defaults operations schedule information based on building type.

Internal Loads

Heat gain from internal loads (e.g., people, lights, and equipment) can constitute a significant portion of the utility requirements in large buildings, both from their direct power requirements and the indirect effect they have on cooling and heating requirements. In fact, internal loads can frequently make large buildings relatively insensitive to weather. More importantly, the performance of almost all energy-efficient design alternatives will be impacted either directly or indirectly by the amount of internal load within a building.

HVAC Equipment and Performance

Good information regarding HVAC equipment efficiency will be important to the accuracy of any energy use simulation. eQUEST assumes default HVAC equipment efficiencies according to California's Title 24 energy standard. Where possible, equipment efficiencies specific to each analysis should be obtained, e.g., from the building design engineers or directly from equipment manufacturers. Most HVAC equipment manufacturers now publish equipment performance data on their web sites.

Utility Rates

A great strength of detailed energy use simulation using eQUEST is the ability to predict hourly electrical demand profiles that can then be coupled with full details of the applicable utility rates (tariffs). eQUEST comes with the principal residential and commercial electric and natural gas rates from the sponsoring California utilities. For California locations (weather file selections), eQUEST defaults the rate selection depending on climate zone and on estimated peak electrical demand. Users outside California must create their own utility rate descriptions using eQUEST's DOE-2-derived Building Description Language (BDL) and save these descriptions as text files for eQUEST's use.

Economic Parameters

Energy Design Resources concur with a growing chorus including the U.S. DOE, Federal Energy Management Program and the National Institute of Standards and Technology in recommending life-cycle economics above simple payback methods of economic analysis.

Because energy efficiency investments usually return benefit over the entire life of the building or system, considering their life-cycle impact is most appropriate. Imagine selecting a variable rate mortgage based on no more information than the initial interest

rate. While few would be comfortable ignoring the long range terms of any loan or investment, it is common practice among building developers and designers to recommend building efficiency investments with equal shortsightedness.

HVAC Zoning

HVAC zoning recognizes that load profiles seen by different spaces in a building differ. Identifying those areas with similar load profiles and grouping them under the same thermostat control improves comfort and may reduce energy. For example, imagine measuring indoor air temperatures at many locations throughout a building during hours when the HVAC fans are turned off. Internal gains, solar gains, and envelope gains/losses would cause the temperatures to vary with time. If, after some number of hours or days, carefully examined the temperature histories, grouping together those that shared similar profiles, have effectively grouped together those areas of the building that share similar load characteristics. Each such area or "zone" could, therefore, be adequately controlled by a single thermostat. In other words, HVAC thermal zoning seeks to group together those areas (rooms) in a building that share similar load and usage characteristics, for purposes of control. Of course, this imagined procedure is not how HVAC engineers actually zone any building.

Rather, the rules listed below are followed.

- The same rules apply when zoning a simulation model when modeling existing buildings, refer to the actual zoning indicated by the HVAC plans
- magnitude and schedule of internal loads
- magnitude and schedule of solar gains
- schedule of fan system operations
- outside air requirements
- intended efficiency measures
- location of thermostats called out on the HVAC plans

Currently, eQUEST provides the user with two automatic zoning schemes, one zone per floor, and simple core-vs.-perimeter zoning. Based on this user selection, eQUEST will automatically zone model for us.

Computational Steps in eQUEST

To better understand the results and limitations of eQUEST DOE-2-derived engine; it is helpful to be familiar with the generic computational steps DOE-2 has always gone through in its simulation. Understanding this sequence is important to understanding the detailed reports produced by eQUEST DOE-2-derived engine. See the Detailed Reports section of this tutorial for a brief overview of the available detailed reports.

eQUEST produces intuitive graphical summary results reports. See the Graphical Reports section for more information about eQUEST's summary reports.

Types of Heat Transfer Surfaces in DOE-2

To better understand how an eQUEST simulation views simulation problem, it is useful to recognize that DOE-2 has always had only four types of heat transfer surfaces on its "palette" to use to model the various types of heat transfer surfaces in actual (proposed) building: Light-transmitting surfaces, e.g., windows, glass block walls, sliding glass doors, skylights, etc. - DOE-2 thinks of all of these as the same type of heat transfer surface, i.e., a WINDOW. Exterior surfaces, e.g., opaque exterior surfaces such as exterior walls, roofs, and floors, etc. - DOE-2 thinks of all of these as the same type of heat transfer surface, i.e., an EXTERIOR-WALL. Interior surfaces, e.g., opaque interior surfaces such as interior walls, interior floors, and interior ceilings, etc. - DOE-2 thinks of all of these as the same type of heat transfer surface, i.e., an INTERIOR-WALL. Underground surfaces, e.g., underground surfaces such as basement floors & walls, & slab-on-grade - DOE-2 thinks of all of these as the same type of heat transfer surface, i.e., an UNDERGROUND-WALL. eQUEST automatically provides its

DOE-2 derived simulation engine with the input descriptions it needs, based on easy-to-understand building description.

Table 1

Comparison of Software Tools for Energy Simulation (Crawley, 2005)

| | | DesignBuilder | eQUEST |
|------------------------|-------------------------------------|--|--|
| General details | | | |
| | Import geometry from CAD programs | yes | yes |
| | Export geometry to programs | yes | no |
| | Unlimited zone, system, equipment | yes | yes |
| | Dimming electric lighting controls | yes | yes |
| Heat load calculations | | | |
| | Hourly load calculation | yes | yes |
| | Thermal comfort estimation | yes | no |
| | Automatic design day calculation | yes | yes |
| HVAC | | | |
| | User configured HVAC system | yes | yes |
| | Automatic sizing | yes | yes |
| | Absorption chillers | yes | yes |
| | Air to air energy recovery systems | yes | yes |
| | Seasonal heat and cold storage | no | yes |
| | Individual zone and system control | yes | yes |
| | Natural ventilation | yes | no |
| | Operable windows | yes | no |
| Climatic data | | | |
| | Weather data available with program | yes | yes |
| | Data editing facility | yes | yes |
| Economic evaluation | | | |
| | Life cycle cost analysis | No | yes |
| Reports | | | |
| | Graphical | Yes | yes |
| | Text | yes | yes |
| Cost of software | | license to be purchased | free |
| Web link | | www.designbuldeco.uk | www.doe2.com |

Table 2

EnergyPlus Advanced Modeling Capabilities beyond DOE-2 (Hong, 2008)

| Item | EnergyPlus | DOE-2 (both 2.1E and 2.2 unless otherwise noted) |
|--|--|--|
| HVAC Loads | Uses the heat balance method which is more accurate. Also performs radiant and convective calculations at each surface. Can model thermal mass effect more accurately. Improved ground heat transfer modeling. Anisotropic sky model provides good diffuse solar calculations | Uses the transfer function method with custom weighting factors. This method is an approximation of the heat balance method, is less accurate and more prone to user error through misapplication of weighting factors. Errors are probably the greatest for building envelope components that have thermal mass. |
| Integrated Simulation of Loads and Systems | Building response to thermal loads is calculated simultaneously with system operation. This expands the range of conditions that can be analyzed to include ones where the building temperatures are not always in control (e.g., natural ventilation, undersized systems). Feedback from HVAC system operation can affect building loads. | Building response to thermal loads is calculated independently of system operation. Load calculations assume building temperatures are in control. Limits applicability of simulation to mechanically conditioned spaces. Limited feedback from HVAC system operation affects building loads and zone temperatures. This prevents DOE-2 from accurately simulating systems and heat transfer where zones are under heated or under cooled. |

| | | |
|----------------------------------|--|---|
| Radiant Exchange | <p>Explicitly models radiant exchange between surfaces. Users have control over solar, visible, and thermal absorptance and emittance for each surface. Surface temperature is a factor in heat transfer.</p> <p>It should be noted that the program uses simplified calculation in lieu of explicit view factors that account for area and orientation of surfaces.</p> | <p>Models radiant exchange only through combined radiation / convection coefficients applied to each surface.</p> <p>The convection and radiant heat transfer do not vary with surface temperature for opaque surfaces.</p> |
| Thermal Comfort | Can develop surface temperatures for consideration of radiant comfort. | Cannot directly model zone thermal comfort as it cannot develop surface temperatures. |
| HVAC Systems | <p>Systems are built up out of fundamental components. This is a more flexible and robust approach to specifying system characteristics. While the process to specify an HVAC system is more complex, templates and wizards help simplify the process.</p> <p>Through a link to SPARK, custom HVAC equipment component models can be modeled to provide further flexibility.</p> | <p>Systems are pre-designed types. This has several limitations:</p> <ol style="list-style-type: none"> 1) You cannot easily model some systems because there is no pre-designed model for them; 2) Enhancements to the program (like evaporative cooling) have to be implemented on each of the different system types. 3) Only one system can be assigned to a zone. You cannot model a system with a perimeter fan coil for heating and a cooling only VAV box for cooling. |
| Displacement Ventilation Systems | Can model both radiation and thermal stratification through a 3-node stratification model. Both of these are critical elements to displacement systems. | Assumes all zones are fully mixed (uniform temperature throughout), which is not appropriate for displacement ventilation systems. |

| | | |
|--------------------------------------|---|---|
| Under-Floor Air Distribution Systems | Can model UFAD systems for interior and perimeter zones. | Assumes all zones are fully mixed (uniform temperature throughout), which is not appropriate for UFAD systems. Cannot model supply plenums. |
| Radiant Cooling and Heating Systems | Can model radiant cooling and heating systems. | No direct models for radiant cooling or heating systems. |
| Natural Ventilation | Can model natural ventilation with Airflow network which allows wind- and buoyancy-driven airflow calculations to be performed simultaneously with building thermal response and system operations calculations. | Can model simplified natural ventilation via operable windows in a few single zone system types (RESYS, RESYS2, PSZ, and EVAP-COOL). |
| Hydronic Loops | Heating and cooling systems can be separated into distribution loops that can be connected to one another. This provides a much more accurate model of system pumping energy. This can be used for evaluation of alternative hydronic distribution systems like primary-only variable flow, primary/secondary and primary/secondary/tertiary systems. | This feature is only available in eQUEST (DOE 2.2). It is not available in the reference method DOE-2.1E. In 2.2 only limited configurations of constant and variable flow systems are available. |
| Moisture Migration | The combined heat and mass transfer model allows EnergyPlus to model moisture migration and its affect on cooling loads. Neglecting moisture migration can cause errors in sensible and latent heat transfers. | Cannot model moisture migration. |
| Multiple Time Steps | Heating and cooling loads are calculated on a timestep basis and passed through to the HVAC portion of the | Can only calculate loads on an hourly basis. There is also no feedback between loads and |

| | | |
|-------------------------------|--|---|
| | simulation. Loads that are unable to be met by the system are fed back into the engine and result in zone temperature/humidity changes for the next time step. The default time step for EnergyPlus is 15 minutes; however, it can be reduced down to 1 minute. | systems. |
| Air Emission | EnergyPlus can calculate air emissions associated with energy use within a building. This is useful in determining environmental impacts of new energy efficiency measures for code development. | DOE-2 cannot calculate air emissions directly. It has to rely on post-processing. |
| Water Usage | Water usage becomes more and more important for California. EnergyPlus can calculate water usage for buildings. | DOE-2 does not have this capability. |
| Renewable Energy | Can model PV either standalone or BIPV. | DOE-2.2 can model PV. |
| Cogeneration | Can model cogeneration with IC engine, micro CHP, and fuel cells. | DOE-2 cannot model IC engine or fuel cells. |
| Daylighting and Controls | EnergyPlus has detailed daylighting models. | DOE-2 tends to overestimate daylighting benefits. |
| Windows and Shading Controls | EnergyPlus has more shading controls for windows and skylights. | DOE-2 has limited shading controls. |
| Demand Response Controls | EnergyPlus has demand limiting controls for lighting, equipment, and zone thermostat. | DOE-2 has none. |
| Outdoor Lighting and Controls | EnergyPlus can model outdoor lighting and controls | DOE-2 cannot. |
| Green Roof | EnergyPlus can model green roofs. | DOE-2 cannot. |
| Visual Comfort | EnergyPlus calculates visual comfort. | DOE-2 does not. |

Run Time comparisons between EnergyPlus and DOE-2

Compared with DOE-2, EnergyPlus runs much slower. The main reason EnergyPlus runs much slower than DOE-2 is that EnergyPlus does the integrated heat balance calculations for loads, systems, and plant at a loads time step normally around 15-minute, while DOE-2 does sequential calculations from loads to systems to plant at an hour time step. EnergyPlus performs necessary iterative calculations at a smaller time step (down to 1 minute) for HVAC systems in order to achieve HVAC convergent solutions.

When DOE-2 was first developed in late 1970s, the computer computing power was very limited. Even a 50-zone model could take hours if not days to complete an annual run. With today's PC computing power, it was thought that it is not so important to develop simulation programs that run as fast as DOE-2, but rather to develop programs that can do sub-hourly and more accurate building thermal performance calculations in a reasonable amount of time, which lead to the rise of EnergyPlus. But this large simulation runtime is still a significant drawback.

According to a study conducted by Tianzhen Hong (Hong, 2008) at a 15-minute time step, EnergyPlus runs much slower than DOE-2.1E by a factor of 105 for the large office building to 196 for the hospital building. At a 60-minute time step, EnergyPlus still runs slower than DOE-2.1E by a factor of 25 for the large office building to 54 for the hospital building;

however, the EnergyPlus computer run time improves by almost a factor of 4 which corresponds to the reduction of number of time steps per hour from 4 to 1. The primary reason EnergyPlus runs considerably slower than DOE-2.1E is that EnergyPlus performs integrated heat balance calculations for loads, systems and plant at a given time step while DOE-2 does sequential calculations from loads to systems to plant without accounting for feedback from plant to systems or from systems to loads. Consequently, EnergyPlus may require several iterations within each time step in order to reach a convergent solution.

In a study done at IIIT Hyderabad, a concept has been proposed which uses data parallelization to speed up EnergyPlus simulation. Data parallelization is a form of parallelization for computing across multiple processors or multiple computers in a cluster, run under a suitable environment. Data parallelism focuses on distributing the data across different parallel computing nodes by breaking it into smaller chunks, each of which is processed on by the same function, running in parallel on different cores/machines. This is achieved by breaking a simulation with annual Run Period into several simulations of smaller Run Period, each handled by a separate computer. Each computer instead of running an annual simulation, handles a chunk of smaller Run Period, say one month, thus taking lesser time. It has been observed that a speed gain of approximately 6.8 times can be achieved by this method. (Garg, 2010)

Chapter 3

ENERGY MODELING

Building Description

The case building is located in Albuquerque, New Mexico. It is a West facing two storied office building with a total floor area of 17,000 sft. Albuquerque is in Climate Zone 5 and it is in a Dry (B) location.

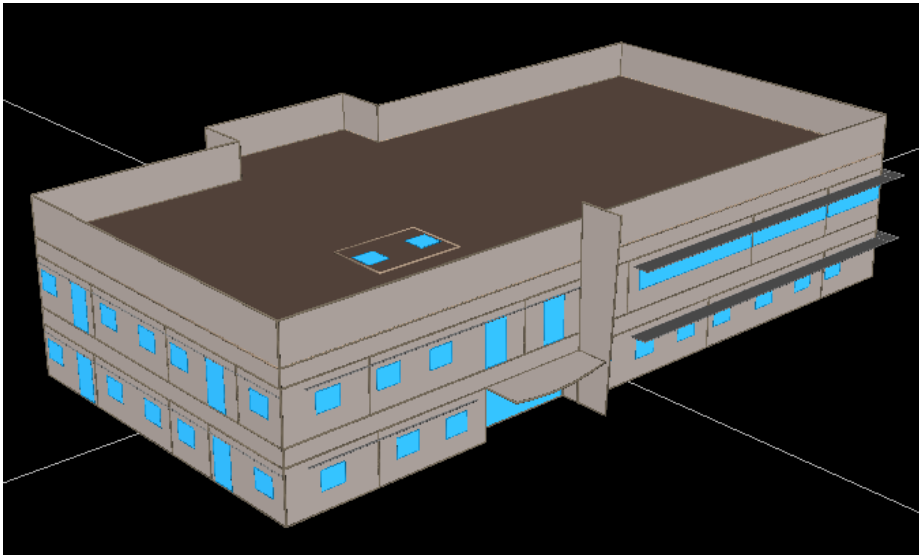


Figure 5. Screenshot of the eQUEST model of the Office building

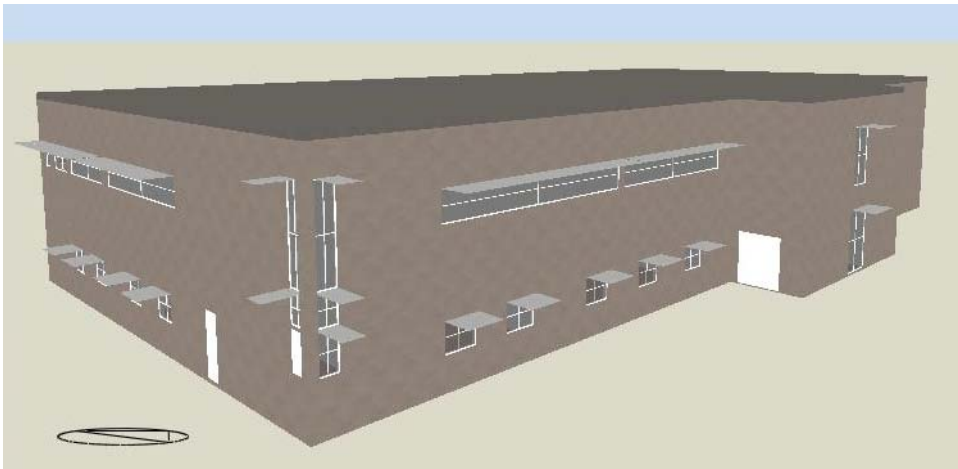


Figure 6. Screenshot of the DesignBuilder model of the Office building

Materials and Construction

The walls are R-19 batt 2 x 6 metal frame spaced on 24-inch centers 1 ½" polystyrene 1" stucco construction and roof is R-30 3/8" built up roof and 5/8" plywood. The floor height is 12' with a floor to ceiling clear space of 9', 3' for the plenum that comprises air conditioning ducts and false ceiling. (See Appendix-B)

Zoning and HVAC

This office building basically has conference rooms, staff offices, management offices, electrical and mechanical rooms. The building has 60 small zones including the Plenum spaces. The building is conditioned with a rooftop packaged VAV system. (See Appendix A)

Table 3
List of zones with areas, occupancy and internal loads

| Zones | Area (sf) | Height (f) | LPD/sf | EPD/sf | Occupancy |
|----------------------------------|-----------|------------|--------|--------|-----------|
| 1st Floor Corridor Spc | 352.6 | 9 | 2.94 | 4.219 | 1.83 |
| 1st Floor Plnm Spc | 8,318.10 | 3 | 1.3 | 1.242 | 0 |
| 2nd Floor Plnm Spc | 8,748.00 | 3 | 1.31 | 1.256 | 0 |
| Breakroom (1011) Spc | 169 | 9 | 1.83 | 4.236 | 0.88 |
| Conference Room (1013) E Spc | 226.6 | 9 | 1.62 | 0 | 1.18 |
| Conference Room (1013) W Spc | 235.8 | 9 | 1.02 | 0.489 | 1.22 |
| Conference Room (2022) Spc | 553.1 | 9 | 3.15 | 2.696 | 3.15 |
| Copy Rm (2029) & Staff Ofc Spc | 305.8 | 9 | 1.18 | 1.133 | 1.74 |
| Copy Room (1027) & Staff Ofc Spc | 356.2 | 9 | 0.61 | 0.584 | 1.85 |
| Dbl Staff Offices (2004, 02) Spc | 482.5 | 9 | 2.08 | 1.989 | 2.74 |

| | | | | | |
|----------------------------------|-------|---|------|-------|------|
| Dbl Staff Offices (2011, 09) Spc | 312.6 | 9 | 3.4 | 7.671 | 1.78 |
| Dbl Staff Offices (2015, 13) Spc | 280.7 | 9 | 1 | 0.747 | 1.60 |
| Dbl Staff Offices (2023, 25) Spc | 274.6 | 9 | 0.52 | 0 | 1.56 |
| Electrical Room (1026) Plnm Spc | 191.2 | 3 | 2.09 | 2.001 | 0 |
| Electrical Room (1026) Spc | 191.2 | 9 | 1.51 | 1.126 | 0 |
| Elevator & Elec. Equip Room Spc | 613.6 | 9 | 1.79 | 1.567 | 0 |
| Elevator/ Storage Spc | 398.9 | 9 | 1.17 | 1.516 | 2.07 |
| Entrance/ Lobby (1000) Spc | 252.8 | 9 | 1.21 | 0.459 | 1.31 |
| IDR Room (1020) Plnm Spc | 238.6 | 3 | 1 | 0 | 0 |
| IDR Room (1020) Spc | 238.6 | 9 | 2.37 | 0 | 0 |
| Management Office (1010) Spc | 422.5 | 9 | 1.3 | 0 | 2.19 |
| Management Office (1056) Spc | 147 | 9 | 0.35 | 0 | 0.76 |
| Management Office (2006) Spc | 151.5 | 9 | 0.13 | 0 | 0.86 |
| Management Office (2050) Spc | 149 | 9 | 1.06 | 0 | 0.85 |
| Mech Chase1 Spc | 20.2 | 9 | 0.85 | 16.89 | 0 |
| Mech Chase2 Spc | 5.9 | 9 | 0.69 | 0 | 0 |
| Mechanical Room (1028) Spc | 248.7 | 9 | 2.4 | 1.357 | 1.29 |
| Restrooms (1st Floor) Spc | 445.4 | 9 | 1.4 | 3.935 | 2.31 |
| Second Floor Corridor Spc | 273.4 | 9 | 0 | 0 | 1.55 |
| Second Floor Restrooms Spc | 396.6 | 9 | 0 | 0 | 2.26 |
| Second Floor Secretary 2 Spc | 275.6 | 9 | 0 | 0 | 1.57 |
| Second Floor Secretary Spc | 212.1 | 9 | 0 | 0 | 1.21 |
| Second Floor Stairwell #1 Spc | 172.5 | 9 | 0 | 0 | 0.98 |
| Second Floor Stairwell #2 Spc | 242.1 | 9 | 2.9 | 1.388 | 1.38 |
| Secretary (1012) Spc | 175.9 | 9 | 2.04 | 2.236 | 0.91 |
| Secretary (1054) Spc | 127 | 9 | 1.51 | 1.268 | 0.66 |
| Staff Office (1018) Spc | 354.2 | 9 | 1.69 | 1.268 | 1.84 |
| Staff Office (2014) Spc | 158.3 | 9 | 2.05 | 1.966 | 0.9 |

| | | | | | |
|----------------------------------|-------|---|------|-------|------|
| Staff Offices (1003, 05, 07) Spc | 311.9 | 9 | 3.15 | 2.407 | 1.62 |
| Staff Offices (1006, 08) Spc | 236.2 | 9 | 3.08 | 2.355 | 1.23 |
| Staff Offices (1014, 16) Spc | 364.9 | 9 | 1.43 | 1.352 | 1.89 |
| Staff Offices (1017, 15) Spc | 304.8 | 9 | 1.34 | 5.008 | 1.58 |
| Staff Offices (1023, 21, 19) Spc | 309.9 | 9 | 0.52 | 0 | 1.61 |
| Staff Offices (1034, 32, 30) Spc | 395.9 | 9 | 1.49 | 1.298 | 2.05 |
| Staff Offices (1036, 38) Spc | 367.2 | 9 | 1.52 | 1.28 | 1.91 |
| Staff Offices (1052, 46) Spc | 553.2 | 9 | 2.76 | 2.115 | 2.87 |
| Staff Offices (1058, 60, 62) Spc | 499.5 | 9 | 2.85 | 1.365 | 2.59 |
| Staff Offices (1064, 66, 68) Spc | 493.8 | 9 | 1.48 | 1.247 | 2.56 |
| Staff Offices (2000, 62) Spc | 361.9 | 9 | 1.74 | 1.306 | 2.06 |
| Staff Offices (2001, 03, 05) Spc | 372.8 | 9 | 1.47 | 1.28 | 2.12 |
| Staff Offices (2010, 12) Spc | 331.7 | 9 | 2.04 | 1.37 | 1.89 |
| Staff Offices (2016, 18, 20) Spc | 484.5 | 9 | 1.53 | 1.143 | 2.76 |
| Staff Offices (2021, 19, 17) Spc | 315.5 | 9 | 1.79 | 1.358 | 1.79 |
| Staff Offices (2034, 32) Spc | 323 | 9 | 2.32 | 3.238 | 1.84 |
| Staff Offices (2040, 38, 36) Spc | 478 | 9 | 1.34 | 0 | 2.72 |
| Staff Offices (2046, 44) Spc | 411.9 | 9 | 0.66 | 0 | 2.34 |
| Staff Offices (2052, 54) Spc | 326 | 9 | 0.1 | 0 | 1.85 |
| Staff Offices (2056, 58, 60) Spc | 489 | 9 | 0.67 | 0 | 2.78 |
| Stairwell #1 Spc | 242.3 | 9 | 1.04 | 0.339 | 1.26 |
| Stairwell #2 (1042) Spc | 234.9 | 9 | 0 | 0 | 1.22 |

Building schedules and operations

The schedules and operating hours for the models are very comprehensive. The building has different schedules for Monday to Thursday and one for Friday and different schedule for weekends and holidays

Energy modeling in eQUEST

The eQUEST model of the office building used in this study was previously developed by a group for studying the performance of the building. It was calibrated against the utility data for a period of one year i.e. August 1st 2004 to July 31st 2005. A custom weather file was created by collecting the onsite weather data for that period of time.

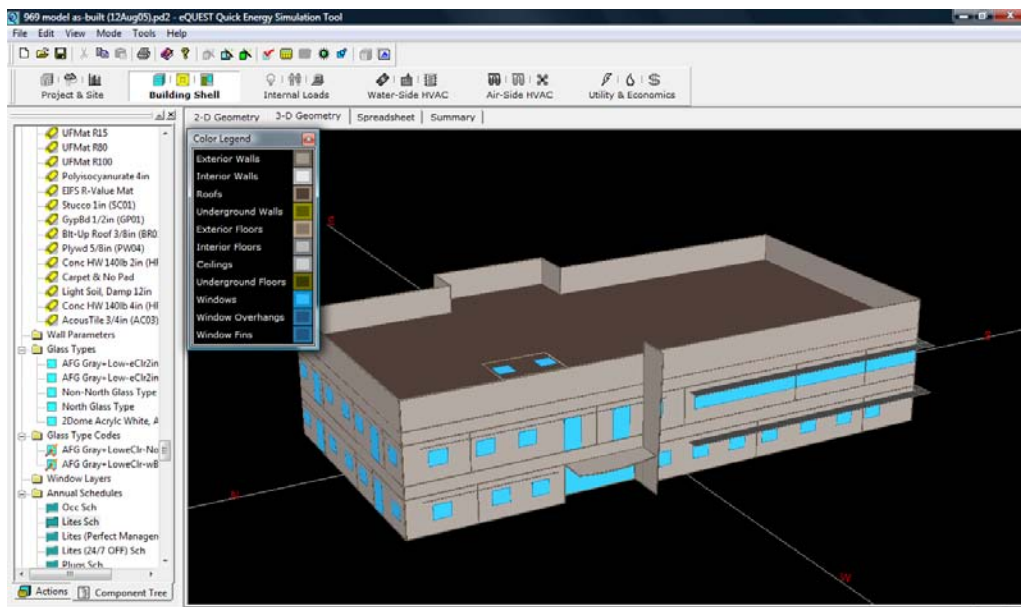


Figure 7. Screenshot of the energy model of the office building in eQUEST

Energy modeling using EnergyPlus

Data Collection

The data for modeling the office building in EnergyPlus was extracted from the eQUEST model that was previously developed by a group for the study of the performance of the building.

DesignBuilder

To model the building in EnergyPlus, initially DesignBuilder software which is the most popular front end for EnergyPlus was used. It was relatively easy to learn this software based on the experience of having worked on eQUEST before. After developing the basic 3D model from the CAD drawings it was easy to assign basic materials, constructions and schedules since it comes with extensive data templates for simulation inputs such as typical envelope construction assemblies, lighting systems, and occupancy schedules. But assigning a HVAC system to the model was a difficult task since DesignBuilder couldn't model the rooftop packaged VAV system that was used in the actual building.

After spending a while trying to figure out a way to model the Rooftop packaged VAV system in the building, the model was sent to the EnergyPlus support group to include the HVAC system in it. The EnergyPlus support group was kind enough to update the model with the HVAC system in it and return the model to me.

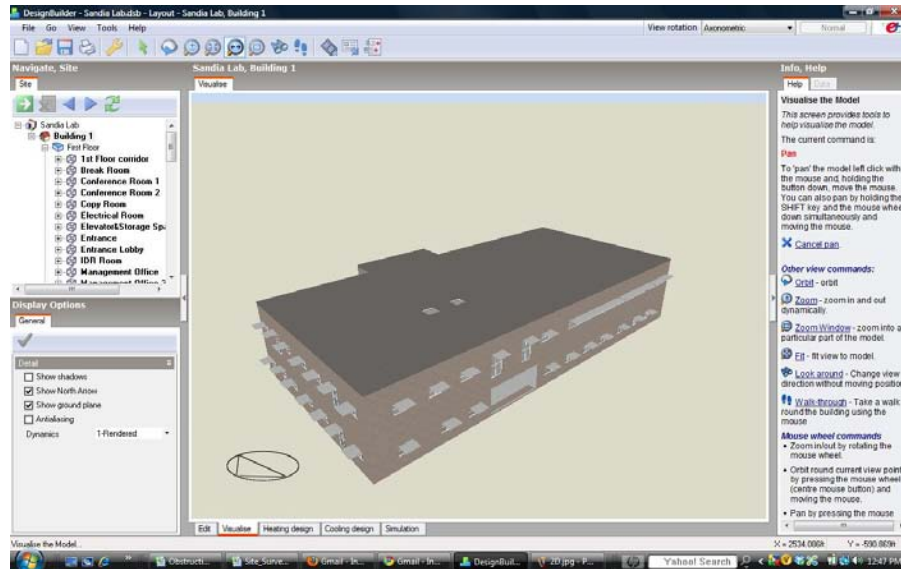


Figure 8. Screenshot of the energy model of the office building in DesignBuilder (DesignBuilder, 2007)

Open studio

The model developed in the DesignBuilder with the integrated HVAC system was given in the EnergyPlus (.IDF) format. To visualize the file and edit the building geometry, Google Sketch Up with an Open Studio plug-in was used. This free plug-in allows us to launch EnergyPlus simulations, assign some attributes and view the results without leaving the Google Sketch Up 3D drawing program. OpenStudio allows us to import the .IDF file and edit surfaces and zones in the file. Using open studio one can match interzone surface boundary conditions, add internal gains and simple outdoor air for load calculations and can set and change default constructions and assign daylighting controls. Though the

OpenStudio plug-in makes it easier to visualize the geometry and do some basic editing, it doesn't yet handle all critical input objects. Some editing of the input file was required to be done outside of SketchUp.

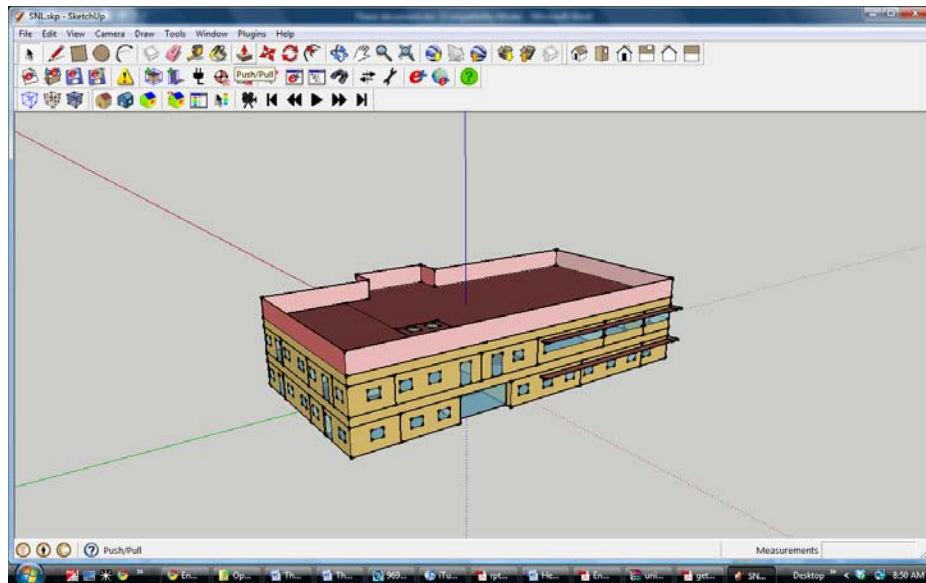


Figure 9. Screenshot of the energy model of the office building in Google Sketch Up with Open Studio Plug-in

IDF Editor

Since Open Studio is not yet developed to the level of being a full fledged front end for EnergyPlus, some of the text file editing was required to do using an IDF Editor. EnergyPlus comes with several utilities to help create input files and run simulations. IDF Editor is one such utility in which any EnergyPlus object may be viewed and edited using a spreadsheet-like grid.

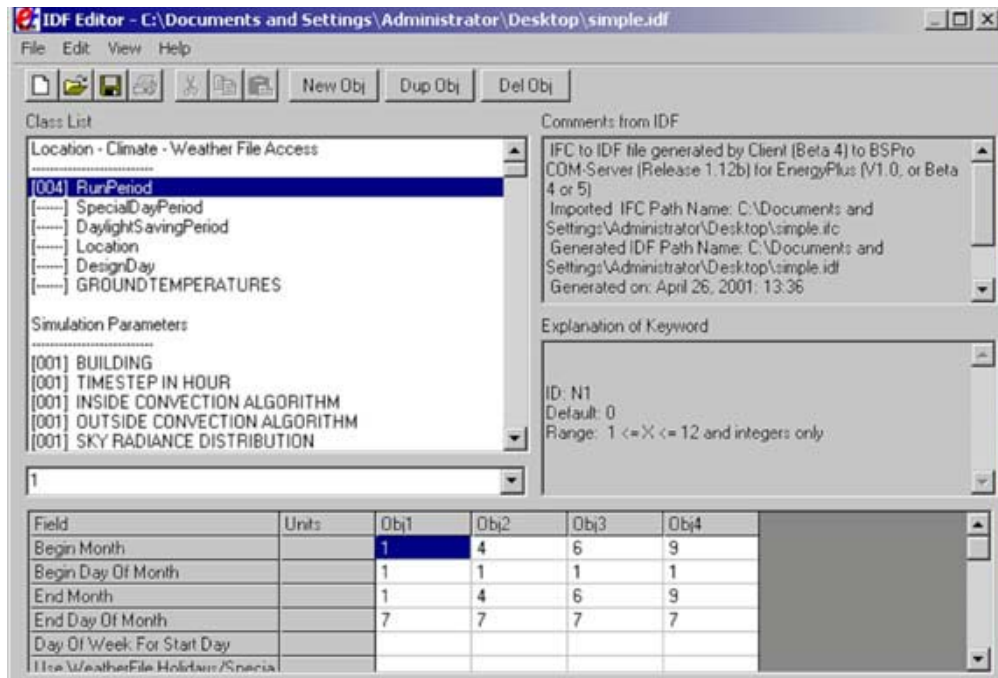


Figure 10. Screenshot of IDF Editor

Using the IDF editor the properties for HVAC system were assigned and the schedules were corrected for errors. Finally the model was ready for simulation by the end of this stage.

Creating the custom weather file for EnergyPlus

The custom eQUEST weather file in .bin format of Albuquerque, New Mexico with the onsite measurements for the period August 1st 2004 to July 31st 2005 was used to create a custom weather file in .epw format for EnergyPlus. This was done using the free weather converter program that comes with the EnergyPlus software package.

RESULTS

Simulation Program Outputs

All the major programs offer the following output includes:

The input data: The report usually repeats the input data for ease of review. This includes data drawn from the program's data libraries. For example, the output may indicate the outside air temperature and humidity that were assumed for each hour.

Building loads: Loads are divided into heating, cooling, lighting, process, etc. Some programs may report the components of these loads. For example, cooling load may be divided into solar gain, conduction load, internal heat gain, and latent load. The loads for individual hours may be displayed.

Equipment Sizing data: Normally equipment capacities are selected by using the calculations of peak equipment load. For example, the program may report the peak air flow of air handling units, the peak steam flow from boilers, the peak energy input to individual chillers, etc.

Outputs in eQUEST and EnergyPlus

In eQUEST there are two ways to use output. One is using the reports generated by the program or using the .SIM file (in Windows Explorer in the project directory) that allows us to jump to each relevant

report (the .SIM file is a normal text file). In reports, there is a tab for each report group - Loads, Systems, Plant, and Economics. There are two controls in each tab that apply to hourly reports. Report Frequency: hourly, daily, monthly or yearly can be selected. In EnergyPlus, we can choose the kind of reports we want to look at. Based on the number of reports requested and the detail, the run time varies. After simulation EnergyPlus gives output in different formats from which we get to choose.

Table 4

Comparison of results for eQUEST and EnergyPlus electric consumption

| Electric Consumption (kWh) | eQUEST | EnergyPlus | Difference |
|----------------------------|----------|------------|------------|
| Space Cool | 49273 | 50699 | -3% |
| Vent. Fans | 47441 | 51527 | -9% |
| Pumps & Aux. | 6328 | 2710 | 57% |
| Misc. Equip. | 162641.3 | 162648.5 | 0% |
| Area Lights | 46985.2 | 46980.29 | 0% |
| Total | 324339 | 314549 | -1% |

Note: There is a mismatch in the areas of the zones and a difference of 4% was notice in eQUEST and EnergyPlus. This error occurred due to the way both external and internal walls are considered by DesignBuilder. DesignBuilder considers external wall inside the drawing and internal wall in mid of CAD boundary.

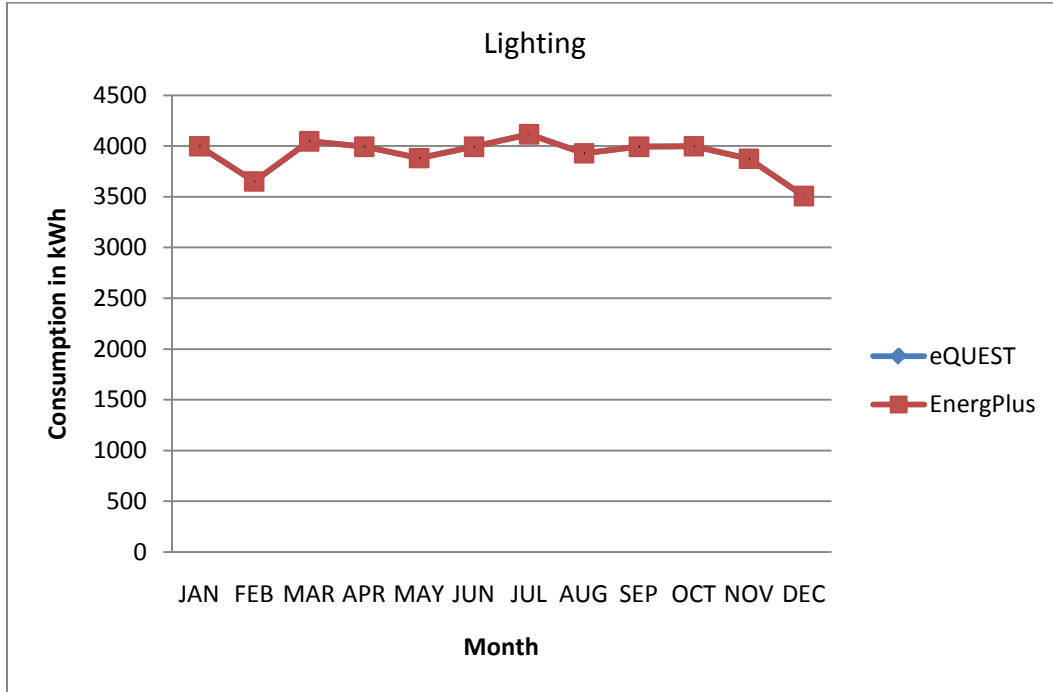


Figure 11. Electricity consumption for lighting

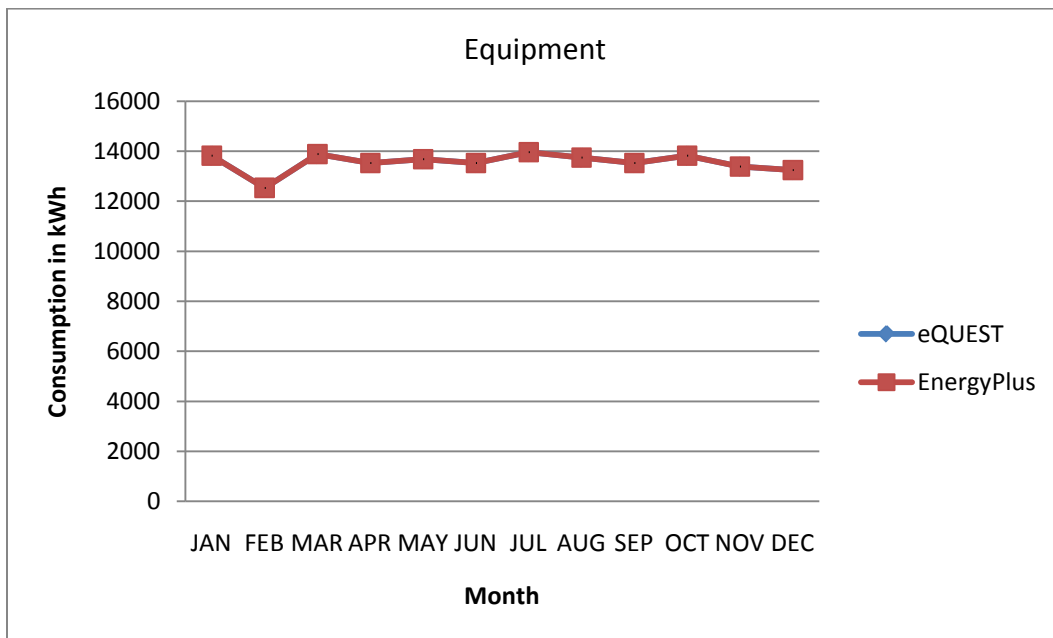


Figure 12. Electricity consumption for equipment

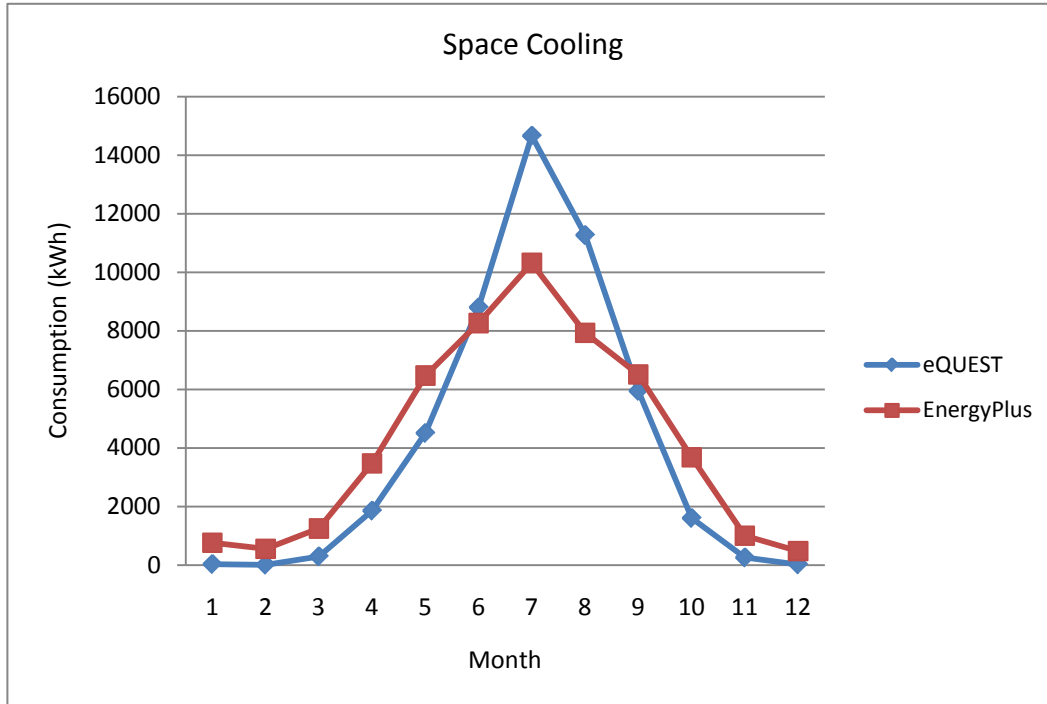


Figure 13. Electricity consumption for space cooling

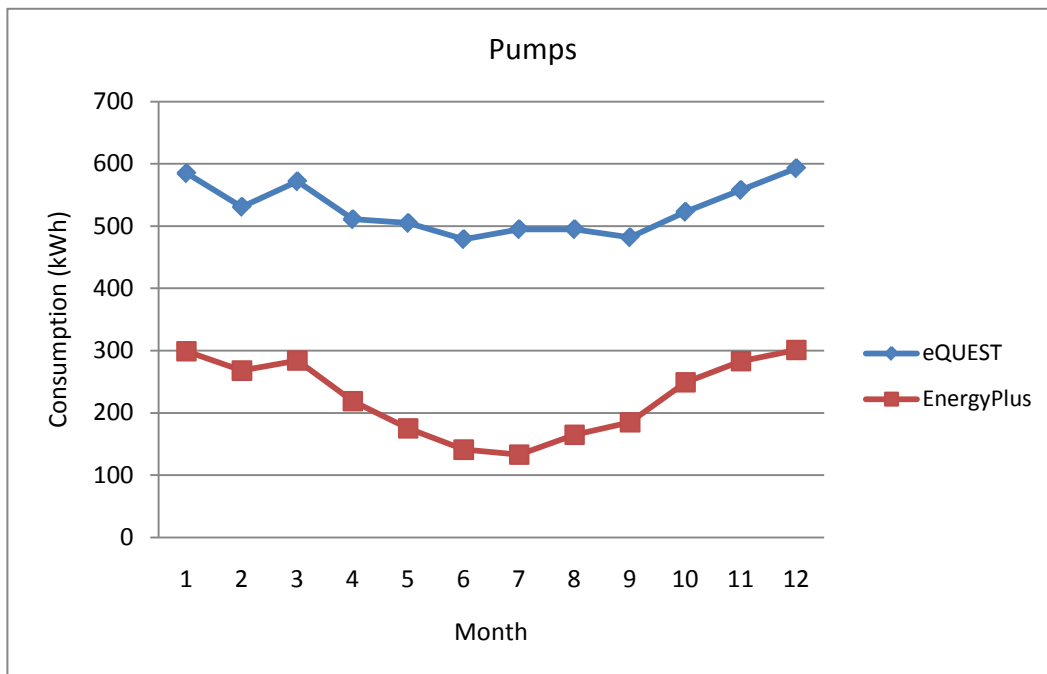


Figure 14. Electricity consumption for pumps

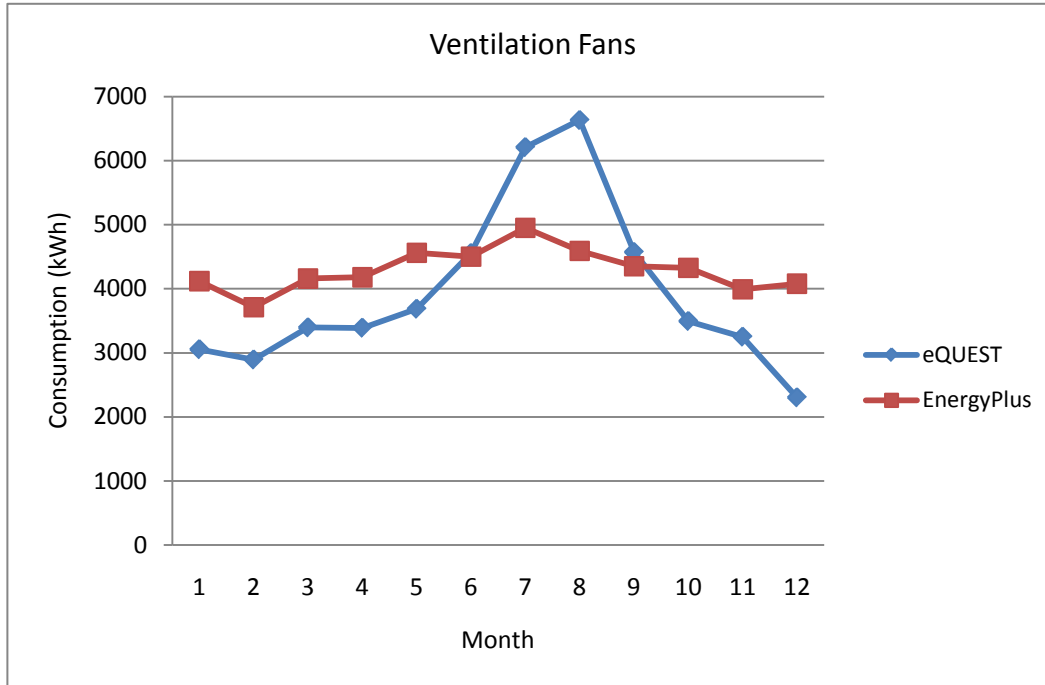


Figure 15. Electricity consumption for ventilation fans

Table 5

Comparison of electricity consumption with the utility data.

| Month | Actual kWh | eQUEST kWh | EnergyPlus kWh |
|-------|------------|------------|----------------|
| Jan | 20,136 | 22436 | 23777.34 |
| Feb | 19,397 | 20641 | 21091.93 |
| Mar | 21,921 | 23926 | 23644.45 |
| Apr | 23,734 | 24270 | 25665.67 |
| May | 28,780 | 27686 | 29476.21 |
| Jun | 33,516 | 32641 | 30057.25 |
| Jul | 39,480 | 39889 | 33704.96 |
| Aug | 36,877 | 37857 | 30683.08 |
| Sep | 30,989 | 29336 | 28522.46 |
| Oct | 24,464 | 24232 | 26763.62 |
| Nov | 21,118 | 22417 | 22818.53 |
| Dec | 20,489 | 20873 | 21781.59 |

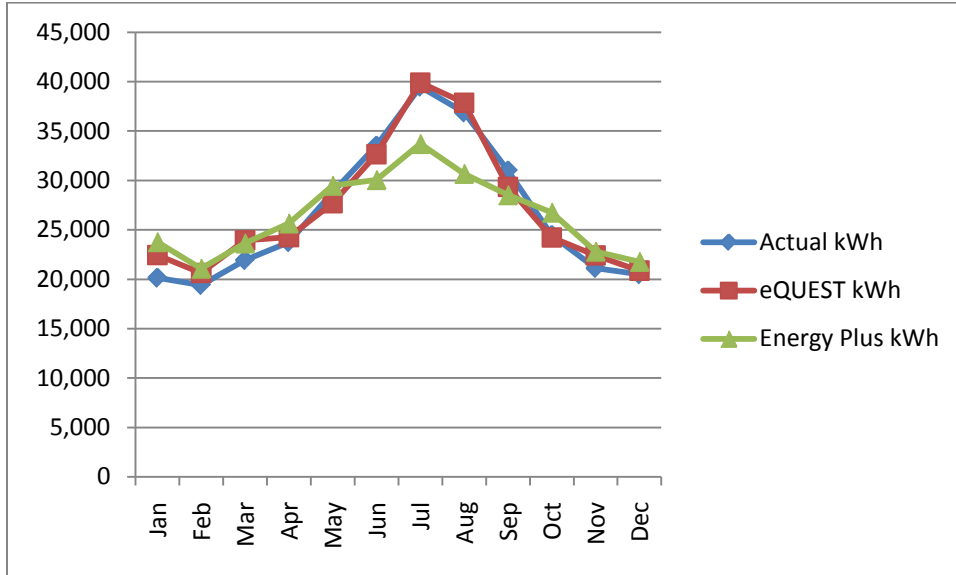


Figure 16. Comparison of electricity consumption results of eQUEST and EnergyPlus with actual consumption in building

Table 6

Comparison of gas consumption with the utility data.

| Month | Actual Therms | eQUEST Therms | EnergyPlus Therms |
|-------|---------------|---------------|-------------------|
| Jan | 535 | 579.28 | 269.97 |
| Feb | 604 | 528.45 | 227.79 |
| Mar | 451 | 511.88 | 220.45 |
| Apr | 326 | 341.51 | 121.28 |
| May | 309 | 304.98 | 60.86 |
| Jun | 305 | 282.78 | 21.18 |
| Jul | 250 | 293.39 | 8.75 |
| Aug | 263 | 306.19 | 21.26 |
| Sep | 290 | 309.1 | 41.03 |
| Oct | 401 | 355.07 | 108.62 |
| Nov | 507 | 540.78 | 217.90 |
| Dec | 694 | 606.42 | 367.67 |

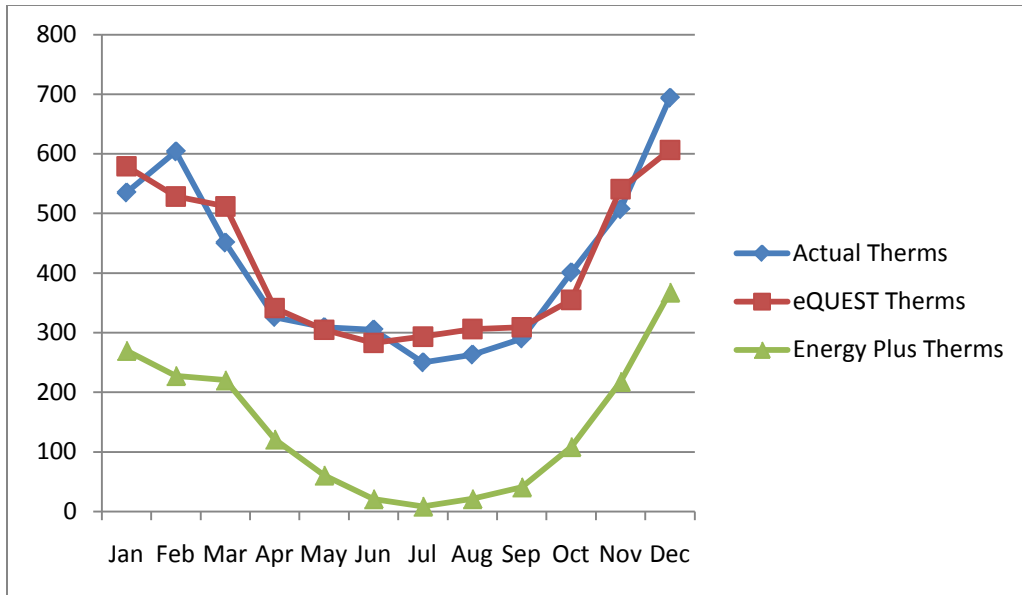


Figure 17. Comparison of gas consumption results of eQUEST and EnergyPlus with actual consumption in building.

Observations and Recommendations

Some of the distinguished building energy simulation tools that exist today are developed by technical researchers, building scientist and HVAC engineers and are not very compatible with architects' working methods and needs. A practitioner needs a single tool that does a whole building analysis right from the inception of design to construction as well as for commissioning of the building after it is occupied. Based on the observations done during the study some recommendations are made to help the practitioners understand the capabilities and limitations of these two tools, thereby allowing them to choose the right tool for their need. Some of these recommendations are aimed at the researchers.

User background and need- The users can be categorized into two groups

- a) Architects, designers and engineers who do not have an in-depth knowledge of building simulation but wish to establish in-house modeling capability. The GUIs for DOE-2 like eQUEST and Visual DOE and for EnergyPlus like DesignBuilder and Open Studio are recommended.
- b) Engineering and modeling specialists whose day to day job it is to carry out design through modeling and analysis. Since this group has a higher level of knowledge and expertise, they can choose from either program based on their need.

Choosing the right tool – Since it was observed that the modeling capabilities are competitive, choosing the right tool should be based on the case. A comparative study of both the tools mentioned in the literature study chapter comes in handy to broadly go through the capabilities to access which could be the right tool for our need. Understanding the strengths and weakness of each tool is crucial in choosing the right tool

Accessibility to the software – DOE-2 and EnergyPlus are free software but a license for the DesignBuilder. DesignBuilder software needs to be purchased after the 30 day trial version, which is with limited modeling capabilities. Open Studio comes as a free plug-in to Google Sketch up software. eQUEST is a freeware. The accessibility and pricing of the software play a key role when a company or an individual has to decide on which software to choose from for establishing their in-house modeling capability. Above all, since EnergyPlus is a developing tool, the user should surely note that there is betterment in the tool every six months with the launch of new version and, hence they might have to upgrade to the new version every six months, which at many times have other implications. Hence, EnergyPlus's key feature of interoperability between two versions is noteworthy.

Ease of learning the software – It is easier to learn eQUEST or DesignBuilder due to its interface and the presentation format of the

software. eQUEST walks the user through a series of screens that allows them to smoothly go through the whole process. One can get a detailed explanation of a particular field by simply right clicking in the field and choosing from the menu. DesignBuilder has a help window that provides tips and wizards guiding the user through the creation of the thermal model. This is especially useful to novice users, as it helps them to better understand the concepts of thermal modeling. It is generally easy to learn these front ends but a one day training or introductory workshop will speed up the learning process. For learning EnergyPlus one needs to have in-depth technical knowledge and have to take a 3-4 day short term course to get a basic understanding of the software. Continued use of the software in day to day energy modeling will improve proficiency.

Documentation and support group – Both eQUEST and EnergyPlus have extensive documentation that supports the learning and modeling process. One can also get active help from the user support groups. And, since EnergyPlus is a developing tool, the user support group is very active. In both the cases, though the example files that are provided with the software help to understand particular cases, it would be helpful to have some documentation of a real time case study of a building that explains the whole process step by step.

Data exchange and interoperability - eQUEST enables DWG imported from a CAD program as a basis for the geometry of the building model. The user has to first redraw the building shape, and then define thermal zoning in a second step. However, eQUEST's ability to modify the geometry after the import is cumbersome and relies on manual change of parameters rather than on modification of objects in a CAD environment. DesignBuilder supports the import of DXF files that can be used as footprints of the building. DesignBuilder allows for multiple footprints, which enables more complex building geometries. The user can select the needed layers and display them at a chosen height. DesignBuilder does not support three dimensional geometry data exchange, since no such functionality is present in the interface. It cannot import EnergyPlus input files (the .idf format) of existing buildings, even though it exports such files.

Modeling capabilities - Creating the geometry, and assigning properties to all the components is a highly complicated and tedious task to work directly in EnergyPlus or a DOE 2 engine. Using the front end like DesignBuilder and eQUEST is relatively easy. eQUEST provides two design wizards, namely the Schematic Design and Design Development Wizards. Both represent well-known stages during design that differ significantly in the level of detail they contain. Both wizards can be used to simplify data input through usage of default parameters. Weather data, geometry, construction material, space types and usage, schedules, and

HVAC systems and components are the major input categories in both the simulation tools.

Note: External wall consideration - eQUEST considers external wall outside the CAD boundary and DesignBuilder considers it internal so while modeling or at the time of converting single line drawing from original CAD one has to consider it, else it will give faulty zone areas. And also the centerline of a wall is to be considered in case of internal partitions in DesignBuilder.

Simulation Run Time - Considering the simulation run time, eQUEST simulates very quickly and EnergyPlus takes a lot of time to simulate which also depends on the complexity of the building and the output reports required. So, for large projects eQUEST is good in terms of the run time of the simulation. EnergyPlus simulation of large buildings might run into few days from few hours. For this case study, while eQUEST took 30 seconds to complete the simulation, EnergyPlus v6 took 35 minutes to complete the simulation when both the models were run at one hour time step. An important point that can be noted here is the simulation runtime difference that was observed between EnergyPlus v5 and v6. The case study building took about an hour to simulate in v5 of EnergyPlus, whereas the same building took 35 minutes in v6. The EnergyPlus model took 50 minutes to run the same simulation at a 15 minute time step in v6.

One can try to reduce the simulation run time in EnergyPlus by trying to keep the model simple for diagnostic analysis and adjust the simulation settings to 1 hour time step especially in the early design stage. Recent studies in this field show that the through data parallelization concept, a single input file of EnergyPlus can be simulated simultaneously on multiple computers, to decrease overall runtime of the simulation.

Energy Efficiency Measures and Parametric runs - In eQUEST, changes can be made in parameters like chiller COP, external wall and roof construction, direction, glazing etc., and the effect of changes can be seen through parametric runs and the energy savings can be compared with base case. Initial and time over investment for each EEM can be inserted as input parameter. These alternative analyses result in annual utility consumption and cost savings for the efficiency measure that can then be used to determine simple payback, lifecycle cost, etc. for the measure and, ultimately, help to determine the best combination of alternatives. These results would also help in the decision making process of the building design. In EnergyPlus each of the changes should be inputted separately and all the simulations together can be run using group simulation options. Updating portions of the multiple files that change and do not change between permutations becomes tedious and error prone and may lead to incorrect conclusions concerning the energy savings of specific measures and more over for every minute change the user needs

to wait for a long time to analyze the results since the simulations run time for each run is high.

Capabilities and limitations specific to software – The modeling capabilities of each of the software might differ. For example: the window opening for natural ventilation can be modeled by EnergyPlus but not by eQUEST. Drury Crawley's paper on 'Contrasting the capabilities of building energy performance simulation programs' provides a quick overview of the basic capabilities of each simulation software. For modeling special cases in EnergyPlus, the user can refer to the example files that come along with the EnergyPlus installation files. Understanding the limitations and common errors of the software are also very important to a practitioner. Identifying the common errors at an advanced stage of modeling can be difficult to correct and is also time consuming. One has to pay careful attention to the changing modeling capabilities that change with the newer versions of the software by closely following the documentation on their websites.

HVAC - eQUEST is good software for the projects where HVAC modeling is required since it supports detailed input parameters for HVAC modeling via performance curves, efficiency, flow, capacity, etc. It precisely calculates the heat gain from occupants and considers both latent and sensible load. The main benefit of eQUEST is that it requires less

simulation time. DesignBuilder only supports compact HVAC system definitions and cannot make use of detailed component-based definitions. The HVAC modeling in EnergyPlus is also very comprehensive. Modeling HVAC through EnergyPlus HVAC templates is easy but it's not in enough detail. The expanded version of the same file is much more detailed and allows us to make the changes individually. High definition of the mechanical system is required for defining it in the expanded input data file.. The level of expertise required to use the tool is rather high and any definition can result in a significant impact in the results.

Subhourly calculations - If in some cases the results are required for less than one hour, only EnergyPlus can be used since eQUEST cannot do calculation for less than one hour time step.

Results and reporting - Both eQUEST and EnergyPlus produce exhaustive results. The EnergyPlus output is text based while eQUEST produces the results in text as well as in graphical format. Though EnergyPlus has some third party programs using with the results can be view in graphical formats, the results format generated by eQUEST are more understandable. There are many report variables in EnergyPlus that one can choose from.

CONCLUSION

This research analyses the building energy simulation tools that run on DOE-2 and EnergyPlus engines. The benefits and limitations of each tool were discussed by describing their functionality, ease of usage, accuracy of results, range of application and run time. The user interfaces for DOE-2 are currently more developed in comparison to the interfaces for EnergyPlus. The lack of user-friendly, mature and comprehensive user interfaces limits the usage of building energy performance simulation in practice. Current progress on interfaces to EnergyPlus is promising and is likely to provide adequate user friendliness and functionality in the future.

As outlined in the recommendations, various issues related to energy simulation tools itself need more development and research to improve the value and accuracy of energy simulation. The strength of energy simulation today is the comparison of different design alternatives rather than predicting absolute energy consumption values. With additional research and development, these tools could also provide more accurate absolute values and provide many additional benefits to their users.

The development of the example building modeled in this research demonstrates the typical and frequently encountered problems related to building energy performance simulation. Energy performance simulation

tools are used throughout the life cycle of the building, i.e. during all stages of the design and construction of the building as well as during the commissioning and operations phase.

As observed in this study eQUEST is easy to use and quick in producing results that would help in the decision making process during the design phase. On the other hand EnergyPlus aids in modeling complex systems but consumes more time. The choice of simulation program might change depending on the usability and applicability of the program to our need in different phases of a building's life-cycle. Therefore, it makes sense if a common front end is designed for both the simulation programs like eQUEST and EnergyPlus thereby allowing the user to select either the eQUEST engine or the EnergyPlus engine based upon the need in each particular case.

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APPENDIX A
ZONE SUMMARY

Table 7
Zone Summary

| Room name | Area [m2] | Conditioned (Y/N) | Volume [m3] | Multipliers | Gross Wall Area [m2] | Window Glass Area [m2] | Lighting [W/m2] | People [m2] per person | Plug and Process [W/m2] |
|-------------------------------|--------------|----------------------|----------------|-------------|----------------------------|------------------------------|--------------------|------------------------------|-------------------------------|
| ELECTRICAL ROOM (1026) | 15.74 | Yes | 43.18 | 1.00 | 16.90 | 3.89 | 15.8177 | 9.29 | 0.0000 |
| 1ST FLOOR CORRIDOR | 31.90 | Yes | 87.50 | 1.00 | 6.04 | 4.46 | 3.8560 | 17.93 | 0.0000 |
| MECHANICAL ROOM (1028) | 21.04 | Yes | 57.71 | 1.00 | 20.68 | 3.89 | 11.8352 | 17.93 | 0.0238 |
| STAFF OFFICES (1034 32 30) | 34.20 | Yes | 93.82 | 1.00 | 25.70 | 3.20 | 20.7315 | 17.93 | 18.1291 |
| STAFF OFFICES (1036 38) | 32.45 | Yes | 89.02 | 1.00 | 16.30 | 2.16 | 17.0714 | 17.93 | 12.7265 |
| STAIRWELL 2 (1042) | 19.35 | Yes | 53.09 | 1.00 | 25.12 | 3.19 | 6.3042 | 17.93 | 0.0000 |
| STAFF OFFICE (1018) | 30.72 | Yes | 84.26 | 1.00 | 19.93 | 3.53 | 7.0322 | 17.93 | 6.7392 |
| ELEC ROOM (1020) | 20.20 | Yes | 55.41 | 1.00 | 24.02 | 0.00 | 27.9716 | 9.29 | 0.0000 |
| MANAGEMENT OFFICE (1056) | 11.79 | Yes | 32.34 | 1.00 | 19.30 | 1.07 | 36.6423 | 17.93 | 52.5884 |
| STAFF OFFICES (1052 46) | 49.41 | Yes | 135.53 | 1.00 | 17.15 | 2.16 | 11.1926 | 17.93 | 8.3590 |

| | | | | | | | | | |
|-------------------------------|-------|-----|--------|------|-------|-------|---------|-------|----------|
| SECRETARY (1054) | 10.56 | Yes | 28.96 | 1.00 | 10.24 | 2.13 | 40.9268 | 17.93 | 92.2748 |
| STAFF OFFICES (1058 60 62) | 43.93 | Yes | 120.51 | 1.00 | 25.47 | 3.24 | 14.7736 | 17.93 | 14.1135 |
| STAFF OFFICES (1023 21 19) | 29.43 | Yes | 80.74 | 1.00 | 0.00 | 0.00 | 22.0163 | 17.93 | 21.0650 |
| COPY ROOM (1027) | 33.25 | Yes | 91.20 | 1.00 | 0.00 | 0.00 | 15.0088 | 17.93 | 42.1690 |
| STAFF OFFICES (1017 15) | 28.53 | Yes | 78.28 | 1.00 | 0.00 | 0.00 | 25.6528 | 17.93 | 14.5085 |
| STAFF OFFICES (1064 66 68) | 43.65 | Yes | 119.74 | 1.00 | 27.43 | 3.20 | 14.8228 | 17.93 | 14.2042 |
| CONFERENCE ROOM (1013) W | 21.87 | Yes | 60.00 | 1.00 | 0.00 | 0.00 | 12.6194 | 17.93 | 16.3229 |
| CONFERENCE ROOM (1013) E | 21.19 | Yes | 58.13 | 1.00 | 0.00 | 0.00 | 12.9295 | 17.93 | 4.9075 |
| ELEVATOR STORAGE | 37.02 | Yes | 101.54 | 1.00 | 0.00 | 0.00 | 7.4294 | 17.93 | 0.0000 |
| BREAKROOM (1011) | 15.72 | Yes | 43.13 | 1.00 | 0.00 | 0.00 | 9.1581 | 17.93 | 181.5081 |
| ENTRANCE LOBBY (1000) | 23.53 | Yes | 64.55 | 1.00 | 16.31 | 15.87 | 17.4227 | 17.93 | 0.0000 |
| STAIRWELL 1 | 24.57 | Yes | 67.41 | 1.00 | 0.00 | 0.00 | 1.2616 | 17.93 | 0.0000 |
| RESTROOMS (1ST FLOOR) | 41.20 | Yes | 113.01 | 1.00 | 0.00 | 0.00 | 11.4570 | 17.93 | 0.0000 |
| STAFF OFFICES (1006 08) | 20.47 | Yes | 56.14 | 1.00 | 19.24 | 2.15 | 21.1087 | 17.93 | 48.9117 |
| MANAGEMENT OFFICE (1010) | 36.50 | Yes | 100.12 | 1.00 | 27.23 | 4.67 | 11.8092 | 17.93 | 5.6717 |

| | | | | | | | | | |
|-------------------------------|--------|-----|--------|------|--------|------|---------|-------|---------|
| STAFF OFFICES (1003 05 07) | 28.96 | Yes | 79.44 | 1.00 | 0.00 | 0.00 | 22.4116 | 17.93 | 21.4101 |
| SECRETARY (1012) | 15.57 | Yes | 42.72 | 1.00 | 8.35 | 1.07 | 35.5751 | 17.93 | 30.4379 |
| STAFF OFFICES (1014 16) | 32.76 | Yes | 89.87 | 1.00 | 17.57 | 2.14 | 13.1557 | 17.93 | 12.6063 |
| 1ST FLOOR PLENUM | 780.10 | No | 713.32 | 1.00 | 112.91 | 0.91 | 0.0000 | | 0.0000 |
| SECOND FLOOR CORRIDOR | 24.22 | Yes | 66.44 | 1.00 | 10.65 | 0.00 | 7.5557 | 16.35 | 0.0000 |
| CONFERENCE ROOM (2022) | 47.97 | Yes | 131.59 | 1.00 | 33.19 | 3.24 | 11.9872 | 16.35 | 3.9193 |
| STAFF OFFICES (2034 32) | 28.46 | Yes | 78.10 | 1.00 | 16.75 | 5.45 | 17.2517 | 16.35 | 14.5111 |
| STAFF OFFICES (2040 38 36) | 42.24 | Yes | 115.92 | 1.00 | 24.86 | 7.08 | 16.8548 | 16.35 | 14.6769 |
| SECOND FLOOR STAIRWELL 2 | 19.77 | Yes | 54.25 | 1.00 | 25.78 | 2.95 | 6.3731 | 16.35 | 0.0000 |
| STAFF OFFICE (2014) | 12.82 | Yes | 35.18 | 1.00 | 20.34 | 3.53 | 21.4427 | 16.35 | 16.1405 |
| STAFF OFFICES (2016 18 20) | 42.65 | Yes | 116.99 | 1.00 | 25.08 | 2.15 | 16.6946 | 16.35 | 14.5375 |
| MANAGEMENT OFFICE (2050) | 11.80 | Yes | 32.36 | 1.00 | 19.30 | 6.14 | 36.6211 | 16.35 | 17.5476 |
| SECOND FLOOR SECRETARY | 18.20 | Yes | 49.92 | 1.00 | 10.24 | 3.10 | 23.7936 | 16.35 | 26.0466 |
| STAFF OFFICES (2046 44) | 36.51 | Yes | 100.15 | 1.00 | 16.05 | 5.10 | 15.1201 | 16.35 | 56.5085 |

| | | | | | | | | | |
|-----------------------------------|-------|-----|--------|------|-------|------|---------|-------|---------|
| DBL STAFF OFFICES (2004 02) | 42.55 | Yes | 116.73 | 1.00 | 24.66 | 4.69 | 23.1249 | 16.35 | 15.5341 |
| SECOND FLOOR SECRETARY 2 | 24.16 | Yes | 66.29 | 1.00 | 14.44 | 3.61 | 20.4015 | 16.35 | 15.4770 |
| STAFF OFFICES (2010 12) | 29.57 | Yes | 81.12 | 1.00 | 17.14 | 2.14 | 16.6044 | 16.35 | 14.0004 |
| STAFF OFFICES (2001 2003 2005) | 34.20 | Yes | 93.81 | 1.00 | 0.00 | 0.00 | 25.2954 | 16.35 | 35.2966 |
| SECOND FLOOR STAIRWELL 1 | 15.66 | Yes | 57.27 | 1.00 | 0.00 | 2.43 | 7.2802 | 16.35 | 0.0000 |
| SECOND FLOOR RESTROOMS | 37.14 | Yes | 101.89 | 1.00 | 0.00 | 0.00 | 14.2967 | 16.35 | 0.0000 |
| STAFF OFFICES (2000 62) | 32.12 | Yes | 88.11 | 1.00 | 18.61 | 3.62 | 17.2475 | 16.35 | 12.8889 |
| ELEVATOR ELEC EQUIP ROOM | 57.02 | Yes | 156.41 | 1.00 | 0.00 | 0.00 | 1.0699 | 9.29 | 0.0000 |
| COPY ROOM (2029) | 28.47 | Yes | 78.11 | 1.00 | 0.00 | 0.00 | 15.3468 | 16.35 | 14.5040 |
| DBL STAFF OFFICES (2011 09) | 29.15 | Yes | 79.96 | 1.00 | 0.00 | 0.00 | 29.6053 | 16.35 | 22.6757 |
| STAFF OFFICES (2056 58 60) | 43.26 | Yes | 118.68 | 1.00 | 25.07 | 7.42 | 19.0919 | 16.35 | 14.3305 |
| DBL STAFF OFFICES (2023 25) | 25.46 | Yes | 69.84 | 1.00 | 0.00 | 0.00 | 33.9756 | 16.35 | 25.9629 |
| DBL STAFF OFFICES (2015 13) | 25.65 | Yes | 70.35 | 1.00 | 0.00 | 0.00 | 33.7274 | 16.35 | 25.7732 |
| STAFF OFFICES (2052 54) | 29.17 | Yes | 80.03 | 1.00 | 16.91 | 5.34 | 16.8650 | 16.35 | 14.1570 |

| | | | | | | | | | |
|-------------------------------|---------|-----|---------|------|--------|--------|---------|-------|---------|
| STAFF OFFICES (2021 19 17) | 29.62 | Yes | 81.26 | 1.00 | 0.00 | 0.00 | 21.8424 | 16.35 | 20.9309 |
| MANAGEMENT OFFICE (2006) | 12.25 | Yes | 33.61 | 1.00 | 19.66 | 2.14 | 35.2595 | 16.35 | 16.8952 |
| 2ND FLOOR PLENUM | 764.47 | No | 713.35 | 1.00 | 112.91 | 0.00 | 0.0000 | | 0.0000 |
| Total | 3100.17 | | 5708.41 | | 907.51 | 133.06 | 8.3121 | 32.47 | 8.0871 |
| Conditioned Total | 1555.60 | | 4281.73 | | 681.69 | 132.15 | 16.5653 | 16.29 | 16.1169 |
| Unconditioned Total | 1544.57 | | 1426.67 | | 225.82 | 0.91 | 0.0000 | | 0.0000 |

APPENDIX B

MATERIALS AND CONSTRUCTIONS

Table 8
Glass properties

| Glass Type Name | Spec Method | Library Selection | Shading Coefficient | Glass Conductance | Visible transmittance | Outside Emissivity |
|---------------------------------|---------------|------------------------|---------------------|-------------------|-----------------------|--------------------|
| AFG Gray+Low-eClr2inAlFrmNoBrk | Glass Library | AFG Gray+LoweClr-NoBrk | n/a | 1.47 | 0.9 | 0.84 |
| AFG Gray+Low-eClr2inAlFrmwBrk | Glass Library | AFG Gray+LoweClr-wBrk | n/a | 1.47 | 0.9 | 0.84 |
| Non-North Glass Type | Simplified | n/a | 0.44 | 0.36 | 0.45 | 0.84 |
| North Glass Type | Simplified | n/a | 0.44 | 0.36 | 0.45 | 0.84 |
| 2Dome Acrylc White, Alum no Brk | Simplified | n/a | 0.54 | 1.27 | 0.5 | 0.84 |

Table 9
Material Properties

| Material Name | Spec Method | Thickness | Conductivity | Density | Specific heat | Resistance |
|------------------------|-------------|-----------|--------------|---------|---------------|------------|
| EWall Cavity R-value | Resistance | n/a | n/a | n/a | n/a | 9 |
| IWall Cons Mat 2 (5.5) | Resistance | n/a | n/a | n/a | n/a | 5.5 |
| Roof R-Value (R30) | Resistance | n/a | n/a | n/a | n/a | 30 |
| UFMat R6 | Resistance | n/a | n/a | n/a | n/a | 6.5 |
| UFMat R25 | Resistance | n/a | n/a | n/a | n/a | 25.8 |
| UFMat R20 | Resistance | n/a | n/a | n/a | n/a | 19 |
| UFMat R40 | Resistance | n/a | n/a | n/a | n/a | 43 |
| UFMat R30 | Resistance | n/a | n/a | n/a | n/a | 29.1 |
| UFMat R10 | Resistance | n/a | n/a | n/a | n/a | 9.9 |

| | | | | | | |
|----------------------------|------------|-------|--------|-----|------|------|
| UFMat R15 | Resistance | n/a | n/a | n/a | n/a | 14.1 |
| UFMat R80 | Resistance | n/a | n/a | n/a | n/a | 84 |
| UFMat R100 | Resistance | n/a | n/a | n/a | n/a | 100 |
| Polyisocyanurate 4in | Properties | 0.351 | 0.0117 | 2 | 0.22 | n/a |
| EIFS R-Value Mat | Resistance | n/a | n/a | n/a | n/a | 6 |
| Stucco 1in (SC01) | Properties | 0.083 | 0.4167 | 116 | 0.2 | n/a |
| GypBd 1/2in (GP01) | Properties | 0.042 | 0.0926 | 50 | 0.2 | n/a |
| Blt-Up Roof 3/8in (BR01) | Properties | 0.031 | 0.0939 | 70 | 0.35 | n/a |
| Plywd 5/8in (PW04) | Properties | 0.052 | 0.0667 | 34 | 0.29 | n/a |
| Conc HW 140lb 2in (HF-C12) | Properties | 0.167 | 1 | 140 | 0.2 | n/a |
| Carpet & No Pad | Resistance | n/a | n/a | n/a | n/a | 0.75 |
| Light Soil, Damp 12in | Properties | 1 | 0.5 | 100 | 0.25 | n/a |
| Conc HW 140lb 4in (HF-C5) | Properties | 0.333 | 1 | 140 | 0.2 | n/a |
| AcousTile 3/4in (AC03) | Properties | 0.063 | 0.033 | 18 | 0.32 | n/a |

Table 10
Construction Layers

| Layer name | Ins Film Resis | Material1 | Thkness1 | Material 2 | thkness2 | Material 3 | thkness3 | Material 4 | thkness 4 |
|-------------------|----------------|----------------------------|----------|------------------------|----------|----------------------|----------|--------------------|-----------|
| Clg Tile Layer | 0.76 | AcousTile 3/4in (AC03) | 0.063 | - | n/a | - | n/a | - | n/a |
| EWall Cons Layers | 0.68 | Stucco 1in (SC01) | 0.083 | EIFS R-Value Mat | n/a | EWall Cavity R-value | n/a | GypBd 1/2in (GP01) | 0.042 |
| IFlr Cons Layers | 0.68 | Conc HW 140lb 2in (HF-C12) | 0.167 | Carpet & No Pad | n/a | | n/a | - | n/a |
| IWall Cons Layers | 0.68 | GypBd 1/2in (GP01) | 0.042 | IWall Cons Mat 2 (5.5) | n/a | GypBd 1/2in (GP01) | 0.042 | - | n/a |
| Roof Cons Layers | 0.68 | Blt-Up Roof 3/8in (BR01) | 0.031 | Roof R-Value (R30) | n/a | Plywd 5/8in (PW04) | 0.052 | - | n/a |

Table 11
Construction

| Construction name | Spec Method | Absorptance | roughness | U value | Wall parameters | Layers |
|------------------------|---------------|-------------|-----------|---------|-----------------|-------------------|
| EWall Construction | Layers Input | 0.6 | 1 | 0.061 | - undefined - | EWall Cons Layers |
| Ceilg Construction | Layers Input | 0.7 | 3 | 0.377 | - undefined - | Clg Tile Layer |
| IWall Construction | Layers Input | 0.7 | 3 | 0.141 | - undefined - | IWall Cons Layers |
| Roof Construction | Layers Input | 0.5 | 1 | 0.031 | - undefined - | Roof Cons Layers |
| IFlr Construction | Layers Input | 0.7 | 3 | 0.626 | - undefined - | IFlr Cons Layers |
| Dummy U-Value Cons | U-Value Input | 0.7 | 3 | 0 | - undefined - | n/a |
| Sgl Lyr Unins Mtl Door | U-Value Input | 0.7 | 3 | 2.08 | - undefined - | n/a |

